NGT-21-002-080
NGT-80001

A PHOBOS INDUSTRIAL PRODUCTION AND SUPPLY BASE

(NASA-CR-184726) A PRELIMINARY DESIGN ON A PHOBOS INDUSTRIAL PRODUCTION AND SUPPLY BASE Final Report (Texas Univ.) 175 p

N89-70261

Unclas

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A PRELIMINARY DESIGN STUDY BY

THE UNIVERSITY OF TEXAS AT AUSTIN

DECEMBER 8, 1986

A PRELIMINARY DESIGN
ON
A PHOBOS INDUSTRIAL PRODUCTION AND SUPPLY BASE

WRITTEN IN RESPONSE TO
RFP #274L / 174M

SUBMITTED TO
THE UNIVERSITY OF TEXAS AT AUSTIN
DEPARTMENT OF AEROSPACE ENGINEERING
AND ENGINEERING MECHANICS

SUBMITTED
BY
IGS

DECEMBER 8, 1986

EXECUTIVE OVERVIEW

In response to Johnson Space Center's efforts to expand NASA's long term goals in space, the University of Texas at Austin Astronautical Engineering design classes have been concentrating their design efforts on a manned mission to Mars since the Spring of 1985. In the Spring of 1986, the manned Mars mission design effort branched to a preliminary mission to Phobos which examined primary and secondary landing sites on Phobos, EVA capabilities, and a manned Phobos rendezvous vehicle. IGS is currently working on the large scale design of an industrial Phobos base consistent with Johnson Space Center's current, near and long term objectives -- a permanent manned presence in space.

This report contains background information on Phobos, a discussion of materials available on Phobos which will benefit Earth, Earth's Moon, Mars, and the outer planets, and the means of producing the beneficial materials mentioned. Logistical advantages of Phobos over space supply ports such as Earth, Earth's Moon and Mars are examined as well as the unique proximity operations conditions which exist at the surface of Phobos. A large scale configuration of the Phobos base along with the base's deployment sequence of events will be presented. Operational procedures for mining and surface transportation systems in the milli-g environment of Phobos are also discussed. In conclusion, strengths and weaknesses of each major design area are reviewed and recommendations are made on future Phobos project continuations for university disciplines including Chemical, Electrical, Mechanical, Astronautical and Civil Engineering.

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1.0 PROJECT INTRODUCTION

In response to Johnson Space Center's efforts to expand NASA's long term goals in space, the University of Texas at Austin Astronautical Engineering design classes have been concentrating their design efforts on a manned mission to Mars since the Spring of 1985. In the Spring of 1986, the manned Mars mission design effort branched to a preliminary mission to Phobos which examined primary and secondary landing sites on Phobos, EVA capabilities, and a manned Phobos rendezvous vehicle. IGS is currently working on the large scale design of an industrial Phobos base consistent with Johnson Space Center's current, near and long term objectives -- a permanent manned presence in space.

1.1 PROJECT OVERVIEW

The Phobos Base Design Group consists of a Project Manager, a Chief Engineer, two Branch Chiefs and three project Engineers as seen in Figure 1.1. The Project Manager controls the project administrative activities, organization deadlines and milestones, and communications with NASA. The Chief Engineer was appointed over the design branches for proper interaction and coordination of the design effort. The Chief Engineer is responsible for the control of the technical issues in the Phobos base design. The design group is divided into two branches: Mission Operations and Base Configuration. Each design branch has a Branch Chief who is responsible for coordinating activities within the branch.

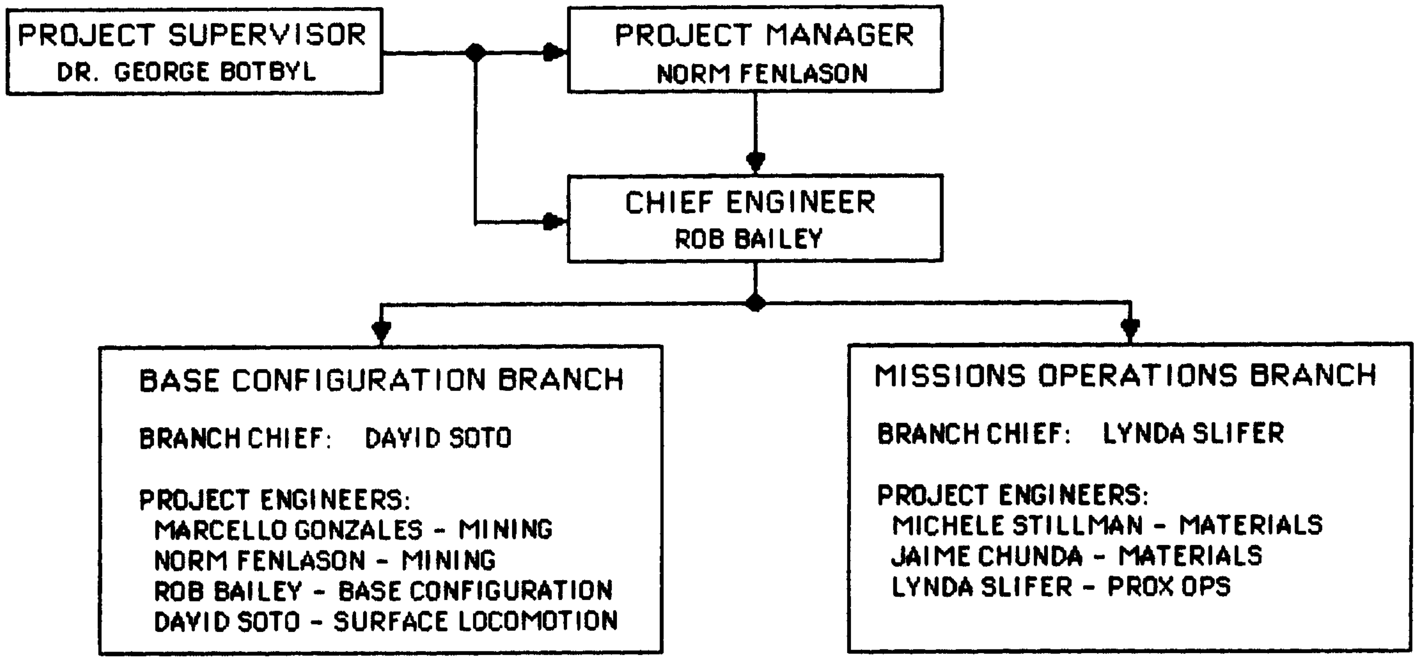


Figure 1.1 - IGS Personnel Organization

Sections 2.0 and 3.0 presents the final analysis of the Mission Operations group. Section 2.0 contains background information on Phobos, a discussion of materials available on Phobos which will benefit Earth, Earth's Moon, Mars, and the outer planets, and the means of producing the beneficial materials mentioned. Section 3.0 discusses the logistical advantage of Phobos over space supply ports such as Earth, Earth's Moon and Mars. Section 3.0 also examines the unique proximity operations conditions which exist at the surface of Phobos.

Sections 4.0 through 6.0 present the final analysis of the Base Configuration group. Section 4.0 defines the large scale configuration of the Phobos base as well as base deployment events sequencing. Section 5.0 discusses the regolith mining operational equipment and procedures. Section 6.0 examines the critical problem of locomotion about the surface of Phobos.

Each section contains a summary of strengths and weaknesses for its particular area of research. The report concludes with a list of recommended Phobos project continuations for university engineering disciplines including Chemical, Electrical, Mechanical, Astronautical, Civil and Nuclear. The remainder of this section will present the argument for establishing an industrial facility on Phobos and the groundrules for the design effort.

1.2 WHY AN INDUSTRIAL FACILITY ON PHOBOS ?

Benefits from mankind's industrialization of space have only been touched compared to the vast potential the extreme edge of our imagination can define. Through an active space program, mankind's unique and progressive ideas may be tapped so that wild imagination may be turned into a new reality. Of course, the industrialization of space must be accomplished in stages. We must first crawl out to a permanent presence in Earth orbit, take our first steps beyond the immediate vicinity of Earth, walk through the solar system, and then run rampant among the stars...but the crawling, stepping, and walking must come first. IGS proposes to establish a permanent autonomous industrial facility on Phobos as a possible first step beyond the Earth.

1.2.1 INTERPLANETARY TRANSPORTATION NODE

The initial steps into the solar system must be planned carefully to facilitate future expansion through the solar system -- Phobos is ideal for this application. Expeditions from Earth to Mars, Jupiter, Saturn and beyond need carry only enough supplies to reach the low gravity environment of Phobos, where supplies such as oxygen, hydrogen, and possibly food could be readily available. Either outbound from Earth or inbound to Earth, Phobos is a crucial node for an interplanetary transportation system free from complications such as atmospheric entry or deep gravity well entry and escape.

1.2.2 EARTH/MARS PROXIMITY MISSION SUPPORT

The delta-V similarities between Earth-based missions to the Moon and LEO and Phobos-based missions to the Moon and LEO suggest the possibility of an Earth independent Moon base and a high altitude Earth space station. A carbonaceous chondrite body with the same mass as Phobos is ultimately capable of producing 72 cubic *miles* of H_2O -- a single cubic mile of water could conceivably support oxygen/hydrogen fuel requirements for the next 40 to 50 years in space. Oxygen and hydrogen are not the only benefits of carbonaceous chondrite bodies; aluminum, magnesium, silicon, iron, and nickel are other resource benefits. With such resources readily available, a Phobos base could produce an unlimited amount of mechanical goods such as material fibers, glass, silicon chips, ceramics, magnets and space truss elements to support all types of space activities.

An extensive industrial facility on Phobos could support the colonization of Mars and the Moon with only periodic, short duration manned support. An autonomous industrial base on Phobos with a manned support capability could solve the supply problems associated with mankind's initial steps beyond Earth.

1.3 DESIGN FOCUS

For any design effort, the problems to be solved must be defined before reasonable solutions to the problems can be developed. The design efforts of the Phobos base design team are focussed on defining problems unique to a milli-g, high vacuum environment and presenting solutions to those problems. The Phobos base design concept presented in this report will cover the following areas:

- materials processing and production;
- proximity operations about Phobos;
- macroscopic scale base configuration;
- mining procedures; and
- surface locomotion.

1.4 ASSUMPTIONS AND GROUND RULES

A set of assumptions and ground rules has been established to define the boundaries of the Phobos base design effort. The assumptions and ground rules presented in this section apply to the specific areas of the design focus.

1.4.1 POWER SUPPLY

Texas A & M's Spring 1986 design team designed a 50 megawatt nuclear power plant with approximately 5 megawatts net power output. The baseline power production capability of the Phobos base will be based on this TAMU design. This power supply will be the main power supply for established mining and materials processing activities. The initial base deployment will require a separate, smaller power facility.

1.4.2 AIRLOCK

The University of Texas Mechanical Engineering Department is designing a minimum volume airlock with a one person capacity to interface with the Phobos Base manned modules.

1.4.3 PRECURSORY MISSION TO PHOBOS

IGS assumes a precursory mission will reveal Phobos as a Type I carbonaceous chondrite asteroid with a 20% by mass composition of water and will confirm Stickney Crater as the primary Phobos landing site. The surface conditions of Stickney Crater will be assumed to be solid rock covered by as much as 200 meters of regolith.

1.4.4 TRANSPORTATION TO MARS

Phobos base transportation from Earth to Phobos, as a whole unit or in sections, is beyond the scope of this design project. Base deployment analysis will begin at the surface of Phobos. The Base will have a manned capability for transport, but manned support (at Phobos) may not be necessary. Propulsion and control systems for orbital transfers are also beyond the scope of this report.

1.4.5 LIFE SUPPORT SYSTEM

The current space station habitation module will be used as a baseline for the Phobos base habitat and laboratory modules sizing requirements. Life support system analysis is beyond the scope of this report.

1.4.6 VEHICLE MASS ESTIMATES

For the delta-V analysis in Sectio 3.0, the following fuel (which will be transported in the form of water) and structural masses will be assumed for Phobos support missions:

a) 200,000 kg transport mass for supply missions;

b) 1,000 kg transport mass for exploration missions;

c) 1000 metric tons of fuel and water for LEO operations per year.

1.5 GENERAL REQUIREMENTS

This sections describes the general requirements that have been defined for a Phobos industrial base.

1.5.1 AUTONOMOUS OPERATIONS

Although the Phobos base will have the capability to support a six man crew, the base will not require full-time manned support. Surface mining and materials processing operations will be fully autonomous to allow Earth/Mars independence or to allow a potential crew to conduct scientific and exploratory missions.

1.5.2 MODULARITY / EXPANDABILITY / RELOCATABILITY

The Phobos base design will be modeled as an industrial production facility, but the baseline configuration will be readily expandable to any type of large scale mission because of the modularity of the system components (i.e. processing, power, habitation, etc.). The Phobos base will also have the capability of expanding and/or relocating its mining operations.

1.5.3 ENTIRE BASE DEPLOYS AS A SINGLE ENTITY

The Phobos base will be assembled as a single entity possessing orbit transfer, surface deployment and production initialization systems to eliminate the need for multiple Phobos rendezvous. This requirement may be relaxed to allow the main power supply to arrive at Phobos prior to the main body of the base. One or two vehicle deployment will depend on crew safety, power plant size, and power plant mass.

1.5.4 MINIMAL MANNED SUPPORT FOR BASE DEPLOYMENT

Base deployment and initialization on the surface of Phobos will be targetted for strictly autonomous operations. A concurrent colonization of Mars would allow remote monitoring of Phobos operations from the surface of Mars

1.5.5 EVA CAPABILITY

The Phobos base will be able to support manned and unmanned EVAs on and above the surface of Phobos for maintenance, exploratory, and mining operations.

1.5.6 MATERIALS PRODUCTION FOR MISSION SUPPORT

The Phobos base will have a maximum capability of producing enough hydrogen/oxygen fuel to support the following missions every year:

a) 1 large scale mission to outer planets ;

b) 12 supply missions to a Mars proximity space station ;

c) 6 supply missions to the surface of Mars;

d) 1 supply mission to an Earth proximity space station ; and

e) 1 supply mission to the Moon.

The number of supportable missions will depend on processing rate, volume, and storage capabilities.

2.0 RESOURCE PROCESSING

This section will describe the physical aspects of Phobos, including its size, orbit about Mars, and its composition and possible resources. The resources will then be evaluated, and possible processing techniques will be explored. Finally, storage facilities will be briefly outlined.

2.1 CHARACTERISTICS OF PHOBOS

As seen in Figure 2.1[1], Phobos (one of the two moons of Mars) is 27km long, 21.4km wide, and 19.2km high (Table 2.1). Stickney crater, which is on the end of Phobos facing Mars, is approximately 10km in diameter. Table 2.1[2] shows Phobos is in a low, almost circular orbit about Mars, with the semi-major axis equal to 9378 km and the eccentricity of the orbit only 0.015. In addition, Phobos revolves almost over the equator of Mars with an inclination of 1.02 degrees, and with a sidereal period of 7 hours 39 minutes 13.85 seconds.

Phobos has low surface gravity which makes it easily accessible to transport to and from the surface. The gravity is only 1cm sec^{-2}, which is one-one thousandth that of Earth. Phobos' density is approximately 2.0g cm^{-3}, and its mass is estimated to be 9.8×10^{15} kg. Because of its low albedo (its albedo is 0.05 : that of Earth's moon is .11) and its low density, Phobos is assumed to be an asteroid that was captured by Mars. The spectrum of Phobos' reflectivity shows that it is similar in composition to a type I carbonaceous chondrite asteroid, which supports the captured asteroid theory.

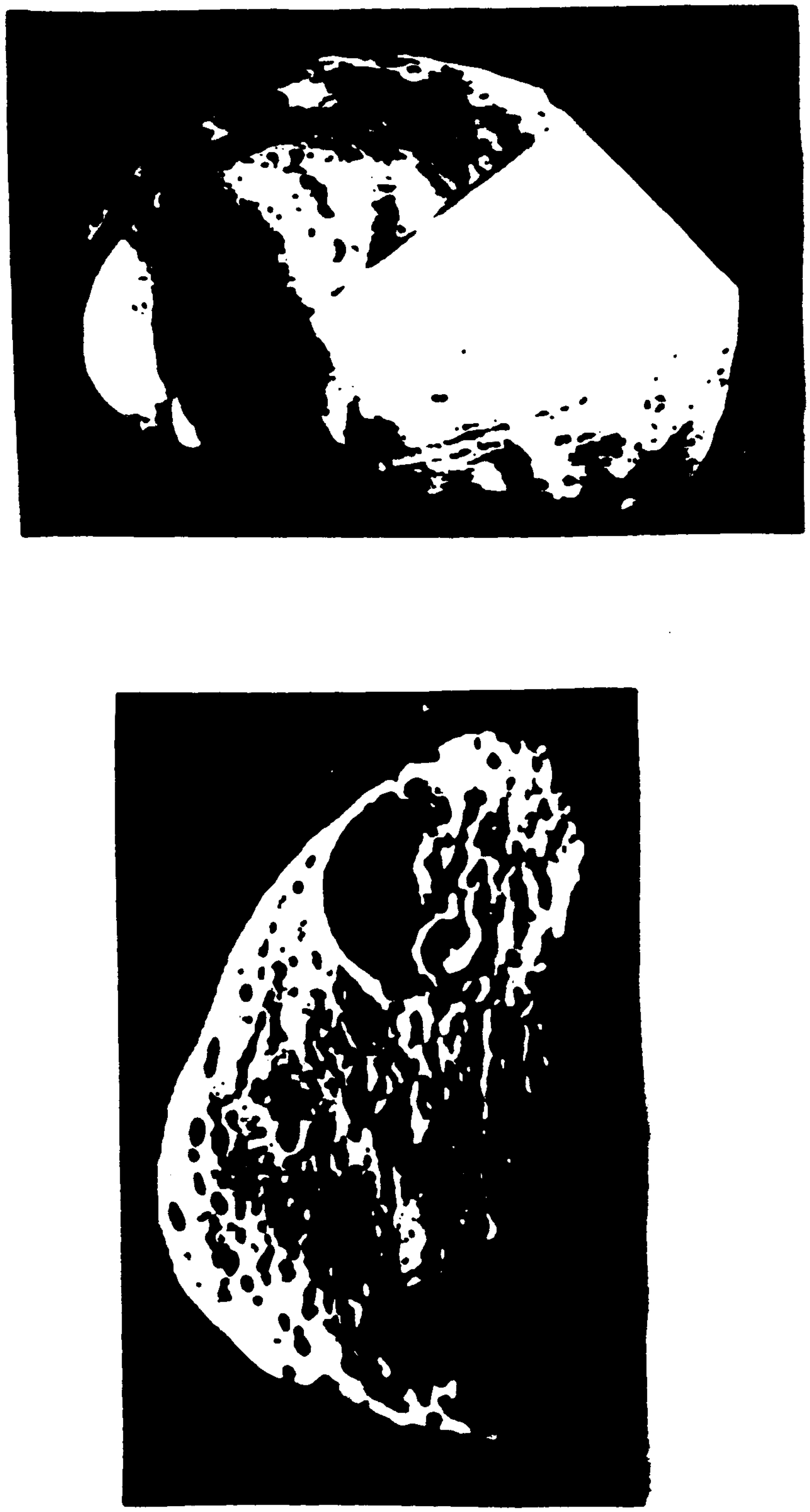


FIGURE 2.1 - Phobos

TABLE 2.1 - Dimensions and Orbital Elements of Phobos

Orbital Elements

•Semi-major axis	9378km (2.76 R_{Mars})
•Eccentricity	0.015
•Inclination (Deg)	1.02
•Sidereal Period	7h39m13.85s

Physical Parameters

•Longest axis	27km
•Intermediate axis	21.4km
•Shortest axis	19.2km
•Rotation	Synchronous
•Density	2.0g cm^{-3}
•Mass	9.8×10^{18} g
•Albedo	0.05
•Surface gravity	1cm sec^{-2}

2.1.1 COMPOSITION OF A TYPE 1 CARBONACEOUS CHONDRITE

The composition of the type I chondrite meteorites which have been analyzed on Earth is presented in Table 2.2.[3] It can be seen that there is an abundance of SiO_2 and H_2O, in addition to other silicates (MgO , FeO) assumed to be present in Phobos.

2.1.2 SURFACE FEATURES

Photometric, polarimetric and radiometric data suggest the surface of Phobos is covered by a deep layer of regolith (weathered rock and sand) which was most likely created by surface weathering and impacts. The cohesion of the regolith (10^4 dyne/cm^2) is lower than that of Phobos as a whole (10^6 dyne/cm^2) which indicates a solid interior lies beneath the regolith.[4] Many of the crater walls display layering, and measurements of those layers suggest regolith thicknesses from 10-200 meters within Stickney crater.[5]

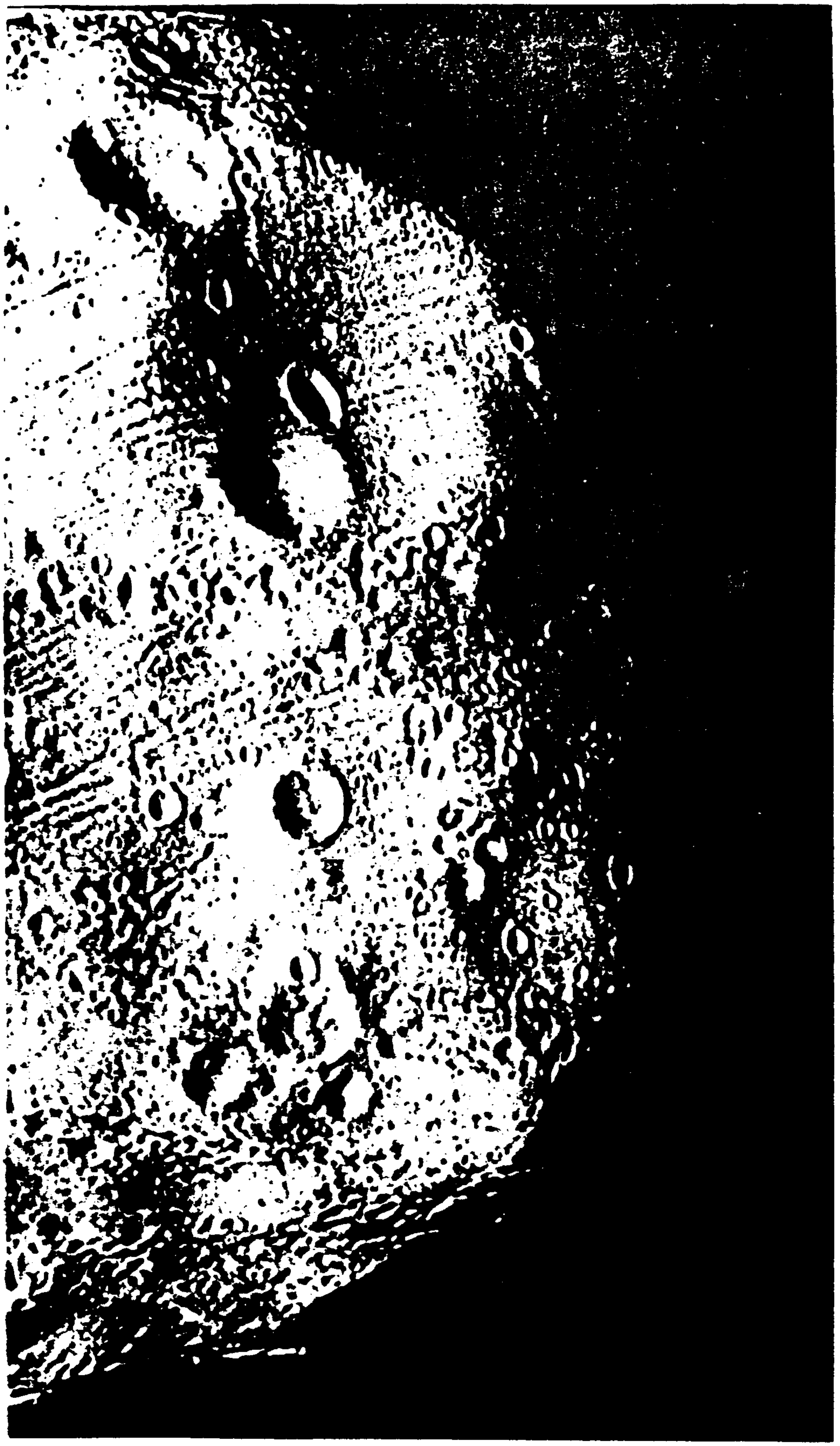


FIGURE 2.2 - Surface Features of Phobos

TABLE 2.2 - Element Composition of Type I - Carbonaceous Chondrite

ELEMENT	PERCENTAGE BY WEIGHT
SiO_2	23.08
TiO_2	0.08
Al_2O_2	1.77
Cr_2O_3	0.28
FeO	10.32
MnO	0.19
MgO	15.56
CaO	1.51
NiO	1.17
Na_2O	0.76
K_2O	0.07
P_2O_5	0.27
H_2O	20.54
Fe	0.11
Ni	0.02
FeS	16.88
C	3.62
Others	3.77

The most unusual surface features of Phobos are (1) the elongated rill-like depressions associated with the crater Stickney, (2) the chains and clusters of irregular elonated craters, and (3) the parallel linear striations or grooves of uncertain origin.[6]

The elongated rill-like depressions can be seen in Figure 2.1. These depressions or troughs originate at Stickney crater and eminate outwards, which suggests the troughs are actually fractures created by the severe metorite impact which formed Stickney crater.

The chains of irregular elongated craters are shown in Figure 2.2.[7] These chains consist of craters 50-200m across, which sometimes cluster into the 'herringbone' pattern characteristic of secondary ejecta. These crater chains are not randomly oriented, but seem to run parallel to Phobos' orbital plane. It is possible that these craters are secondaries which were produced by clumps of ejecta which originally were thrown out at slightly more than the escape velocity of Phobos, went into orbit about Mars, and subsequently reimpacted the surface.[8]

The linear striations or grooves can also be seen in Figure 2.2. These striations are typically 120-200m wide and can be followed individually for more than 5 km. They occur in at least two sets which are not exactly parallel but which do not cross each other. The question remains whether these stiations are more properly gouges or cracks, and they appear to lie in small circles perpendicular to the Mars-Phobos direction. It has been proposed that these striations are either: representations of the layering in Phobos, rows of small impact craters, or cracks resulting from tensional stresses. These stesses would be from the stong gravitational pull of Mars, possibly initiated by the impact which caused Stickney crater.[9]

2.2 VALUE OF RESOURCES

Of the elements assumed to compose Phobos, many would be important when processed into water, propellants, and other materials. These materials would then have applications in interplanetary travel, Mars exploration, base construction, or Earth uses.

For the base on Phobos to be used as a transportation node for inter-planetary travel, the production of water and propellants would be important. Because of the abundance of water on Phobos, a base for water supply could be very valuable and economical. In addition, the water could be processed with electrolysis or thermochemical reactions to yield the propellants, LH_2 and LO_2. These propellants, however, would only be produced for immediate use since their highly reactive and explosive natures make them difficult to store safely. CH_4, Methane, is another propellant which is less reactive and more stable than LO_2 or LH_2, but it yields a lower specific thrust. Methane could also be considered for fuel production.

For the Phobos base to be economically valuable for Earth supply, silicon semi-conductors could be produced with higher precision and lower cost than on Earth. Indeed, Phobos' abundance of silicon and low gravity make it ideal for this application. Also of use on Earth and in space are ceramic magnets ($MgFe_2O_4$). Ceramic magnets have a wide variety of uses in communications for antennae, cassett tapes, deflection transformers in monitor screens, and computer disks.[10]

For use in the Phobos base and in other space structures, Phobos has many material capabilities. The production of iron and Magnesium is feasible as outlined in Section 2.3. Other possible building materials are ceramics, glass and fiberglass which are processed from Al_2O_3, MgO, SiO_2, Na_2O, and CaO. With the exceptions of Na_2O and CaO, the other elements are found in abundance on Phobos. Unfortunately, the manufacture of metals and metal alloys is less feasible since only trace amounts exist of the pure metals. In regolith, most metals eventually become oxidized and so are more difficult (and costly) to extract from their oxidized forms.

2.3 PROCESSING

As stated earlier, Phobos's composition is theorized to be of type 1 carbonaceous chondrite. This suggests that up to 20% of Phobos is water. This water, besides itself being important, can be broken down into cryogenic propellants (LO_2/LH_2) and methane. Storage of this water, the extraction of iron and magnesium, and other possible products will be discussed in this section.

2.3.1 WATER AND FUEL PRODUCTION

Figure 2.3 presents a processing chart for water and fuel production. The process starts with the mined chondrite entering a crusher which physically breaks down the mined regolith so that magnetic separation and transport is easier. The transport of the crushed chondrite to other stages of the process is provided by gas dynamic blowers which need only small pressures, about one millibar, and a carrier gas, such as coarbon dioxide, to move the chondrite particles. Thus, the regolith is transported from the crusher to a magnetic separator which separates out the ferrous compounds (mostly FeO and FeS) and then sends the non-magnetic compounds to the Oven. The Oven utilizes the electrical power from the nuclear reactor to heat up the non-ferrous regolith to approximately 700°C causing the chondrite to release water vapor. However, other gases such as sulfur dioxide, hydrogen sulfide, carbon monoxide, carbon dioxide, and methane will also be released. Therefore, condensers are needed to separate the water vapor from the carbon compound gases. The

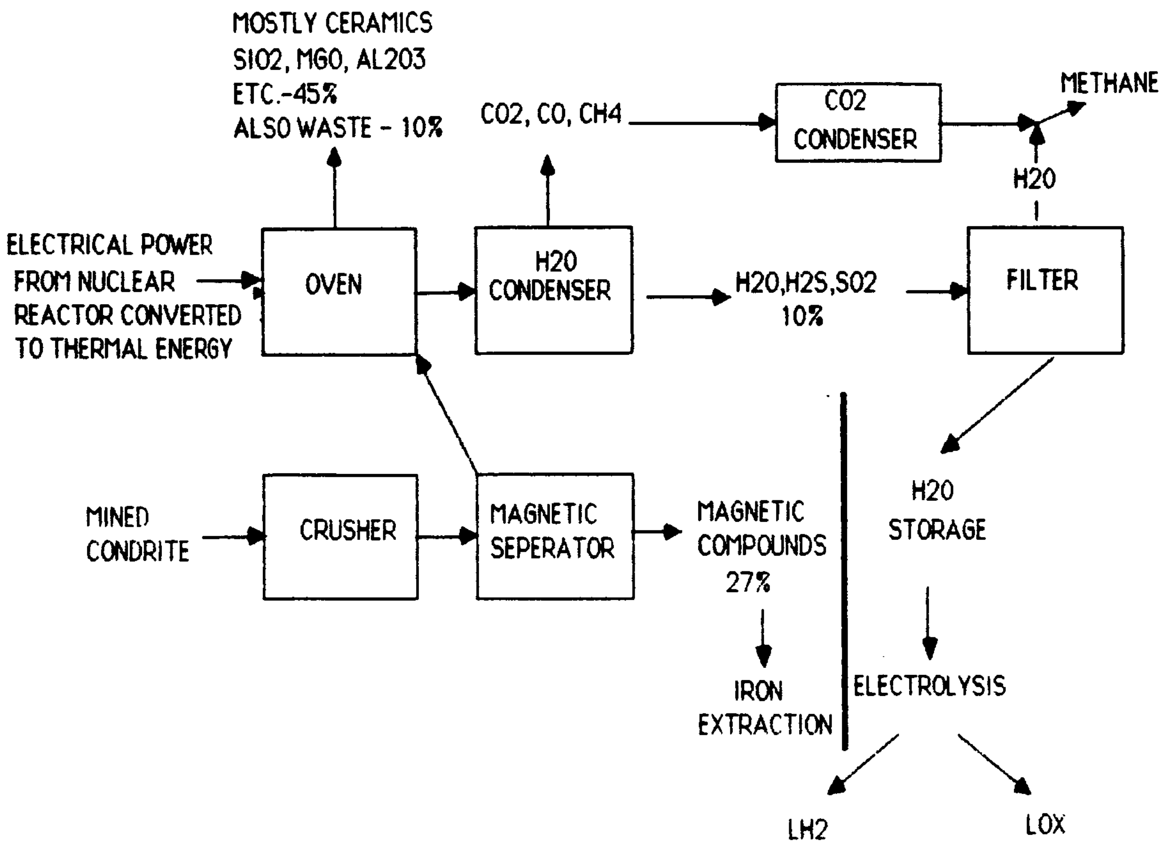


FIGURE 2.3 Water and Fuel Production

condensed water will still contain amounts of dissolved H_2S, and SO_2 which will be filtered out by an activated carbon bed filter -- two filters will be required, one in operation, the other in a regeneration cycle. The water, now purified, can be placed in storage. An electrolysis unit can then be used to produce LO_2, and LH_2, as needed. The unit would use the chemical equation (y is any real number in the equation):[11]

$$(3 + 4.5y)\,H_2O + e = (3 + 4.5y)\,H_2 + (1.5 + 2.35y)\,O_2$$

With water available, methane can also be produced as a fuel. The carbon dioxide can be isolated from the volatile gases that will be realeased by the

Oven by a condenser which uses the distinct vapor point of the gas. A system devised by Ash, Dowler, and Varsi (Ash, et al. 1978) will then combine the liquified gas with water using the following reaction:

$$CO_2 + 2H_2O \rightarrow CH_4 + 2O$$

Methane should be valuable to a Lunar base because of the scarcity of hydrogen on the Moon. Transporting methane instead of water to the Moon would be more economical because the oxygen that is in water would be needlessly transported because oxygen is reatively plentiful there.

2.3.2 POWER AND MASS ESTIMATES

An estimate for power consumption for the water extraction plant was placed near one megawatt. This was based on an estimated 387 kilowatts for the Oven to bring the regolith up to 700°C and about 200 kilowatts for electrolysis. The other 400 kilowatts will needed for blowers,magnetic separator,etc. A mass of 70 metric tons for the plant is also based on a similar plant which produced 600 metric tons of water.[12] More detailed study on the components of the process flow chart are needed in order to produce more precise estimates.

The Phobos mining system can mine 250 mtons of regolith a day that will be transported to the processing system. Several assumptions were made for the efficiency of the processing system at reducing the regolith to its primary compounds: water production will be 50% efficient; electrolysis will be 65% efficient; and all other processing will be 50% efficient. Table 2.3 lists recoverable mass using these efficiency assumptions.

TABLE 2.3 - One Day's Recoverable Mass From 250 mtons/day of Regolith

Compound	10^3 kg
SiO_2	28.85
TiO_2	0.10
FeO	12.90
MgO	19.45
Fe	0.13
Ni	0.025
FeS	21.10
C	4.53
H_2O	25.68
or	
- H_2	1.85
- O_2	14.83

Since the volume of regolith in Stickney Crater is 0.785 km^3, the density of the regolith is 200 kg/m^3, and the mining rate is 250 x 10^3 kg/ day, then it would take 1,721 years to mine out Stickney Crater. So a Phobos base would be in production for a long time.

2.3.3 STORAGE

Water production necessitates water storage; storage for cryogenics is also necessary. The most cost effective solution to this requirement is to use the empty fuel tanks from the orbital maneuvering system as storage vessels. These could accomodate short term LO_2 and LH_2 storage and some of the long term water storage needs. However, additional storage for water will still be necessary.

Figure 2.4 presents a solution to the additional storage problem as a inflatable balloon structure. The balloon is forced down into the regolith and then inflated. Vibration can be used to aid in the effort of forcing the balloon down through the use of a shaker system. The inflation continues until the desired volume is reached. Then a nozzle is inserted which sprays a stiffening cement coating on the inside to give the balloon a permanent structure. This structure is then checked for leaks and sealed so that the structure is gas tight. This structure should provide easily deployable and adequate storage vessels for water.

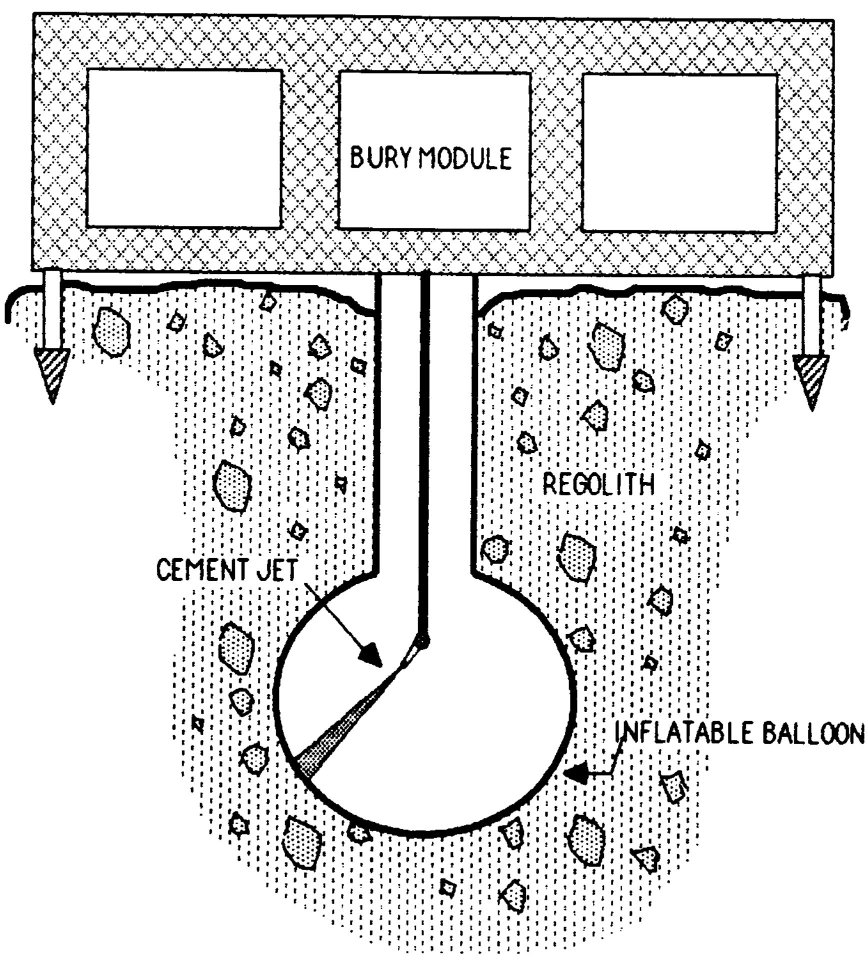


FIGURE 2.4 - Inflatable Balloon Storage Structure

2.3.4 IRON EXTRACTION

Ferrous compounds (FeO and FeS) are relatively plentiful on Phobos. Figure 2.5 shows how iron could be extracted from at least one of these compounds (FeO). The compounds should be easily obtained by a magnetic separator which the regolith is run through prior to water extraction. Silicon will reduce FeO into iron at 1300°C according to equation:[13]

$$2FeO + Si \rightarrow 2Fe + SiO_2 \qquad (1)$$

This reaction requires pure silicon which is not present on Phobos. There are as stated before, plentiful quantities of silicon dioxide. Silicon dioxide can be reduced to silicon at 2300°C by reaction:[14]

$$SiO_2 + 2C \rightarrow Si + 2CO \qquad (2)$$

Pure carbon is required for the above reaction. Phobos's composition should be approximately 3% carbon. However, the simplest method of isolating this carbon would be to reduce one of its gaseous compounds which will be released with water vapor in the Oven of water extraction. The below reaction demonstates how carbon monoxide can be reduced to pure carbon:[15]

$$8.65\,CO + nH_2 = (\text{intermediates}) = 8.65C + (n - 8.65)H_2 + 8.65\,H_2O \qquad (3)$$

Carbon monxide can be isolated in the same manner as carbon dioxide by use of a condenser which takes advantage of carbon monoxide's unique vapor point.

More detailed analysis is needed to complete the iron extraction process. Studies of this and possible steel manufacture are recommended. This process outline was presented to demonstrate that iron can be extracted from Phobos substances.

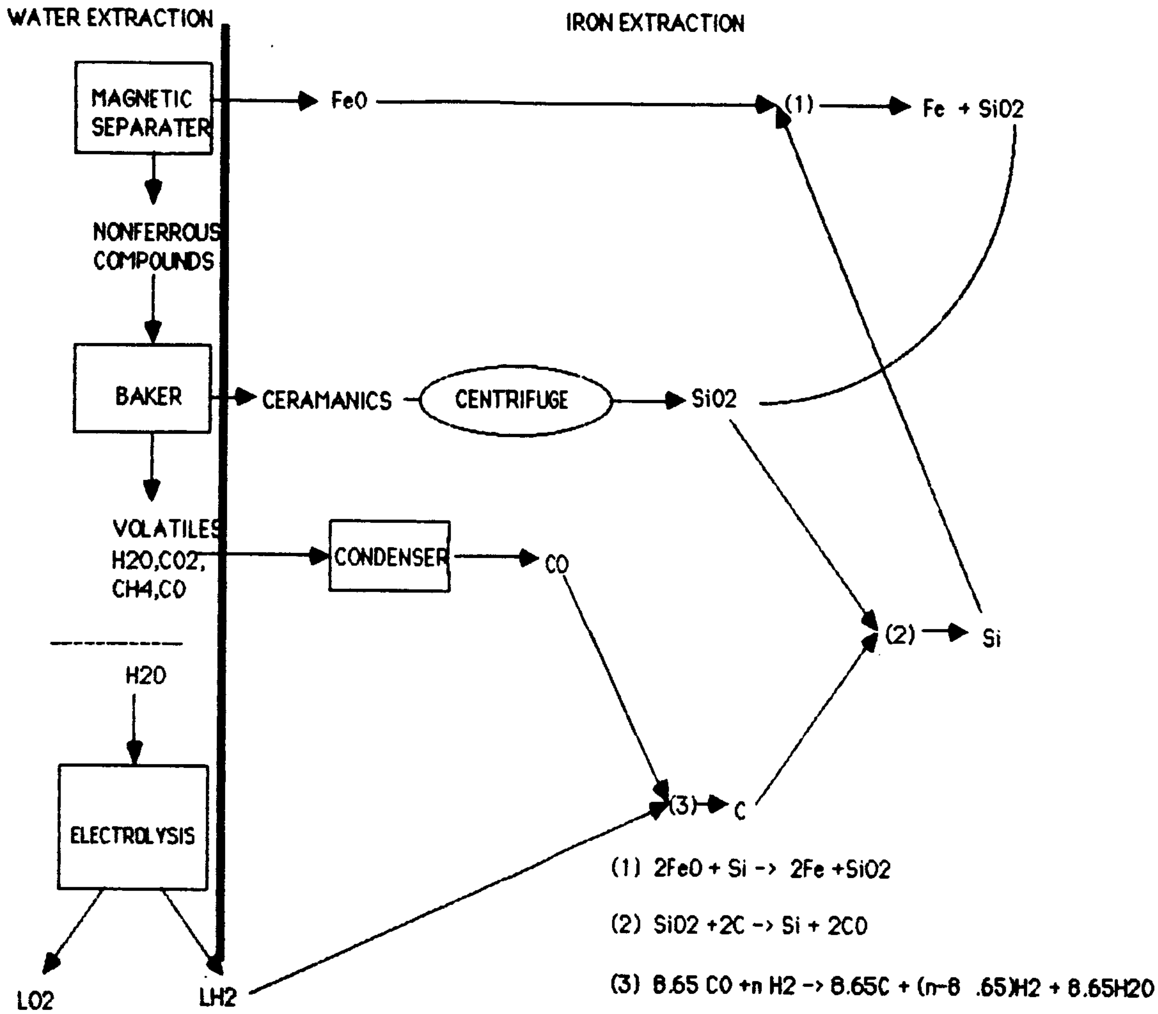


FIGURE 2.5 - Iron Extraction Flow Chart

2.3.5 MAGNESIUM EXTRACTON

Phobos should contain an ample amount of magnesium oxide which can be reduced to pure magnesium. The process would involve heating magnesium oxide, silicon, and calcium oxide to 1200°C to produce vaporized magnesium and solid Ca_2SiO_4. The magnesium vapor is then liquified by a condenser and then poured into molds to form magnesium ingots. The problem of this method is that the quantity of calcium oxide is relatively scarce on Phobos. Glass production, discusseded later, will take all the available calcium oxide.

Another method which requires a higher temperature (2300°C) uses the following reaction:[16]

$$MgO + C \rightarrow Mg + CO$$

The advantage to this method is that carbon is more plentiful than calcium oxide which is required in the first method. This method does require more energy because of its higher temperature but the nuclear reactor should provide an ample amount of energy so that this wil not be a problem. Therefore, this carbon method will be the prefered method. The details of this method requires additional study and it is suggested that specific system be developed.

2.3.6 OTHER PRODUCTS

What other production possiblities exist on Phobos? Table 2.2 shows that silicon dioxide should be 22.6% of Phobos composition. Therefore, glass could be produced since 72% of its composition is silicon dioxide. The other compounds that make up the other 28% are also present on Phobos but not in large quantities. Calcium oxide and sodium oxide make up 1.22% and 0.74% of Phobos respectively. However, some small scale production of glass should be possible using entirely Phobos substance. Research is required to determine specific system to produce glass.

The carbon gases (CO, CO_2, CH_4) that are released during the water extraction process can be processed into ethylene (C_2H_4). Ethylene is the building block of polymers.

If glass and polymers can be produced then their composite, fiberglass, can also be produced. Fiberglass can be useful as a structure material.

As stated eariler, magnesium ferrite will be producible from the vast supplies of FeO and MgO that should be present on Phobos. This magnetic compound is used to make transformers in the communication industry. Another item that might be produced on Phobos is the semiconductor which is made from silicon. The extremely low gravity of Phobos is a advandage when manufacturing the seimconductor chip. Other ceramics also might be manufactured from the vast amount of these compounds present (SiO_2, Al_2O_3, MgO, etc.).

2.3.7 STRENGTHS AND WEAKNESSES

The strength of this section lies in its definition of the materials production capabilities of a Phobos industrial base. The weaknesses of the section include processing waste management, processed materials storage facilities, power requirements, and a lack of detailed production processes.

3.0 ORBITAL MECHANICS

This section includes the aspects of orbital mechanics which must be considered if Phobos is to be presented as a space supply and transportation depot. These aspects include transfer delta Vs and Phobos surface accelerations. The transfer delta Vs are between various points in the Solar System and Phobos, and they show that Phobos will indeed be a good supply base and exploration node. These delta Vs combined with vehicle mass estimates also set fuel requirements for possible missions that can be based from Phobos. Finally, accelerations which will influence surface transportation on and around the Phobos surface are presented.

3.1 SMALL GRAVITY WELL

A Phobos Base would be a good transportation node because Phobos has such a small gravity well. Table 3.1, obtained from Ref. 3.1, shows the relative magnitudes of the escape energies of several locations in the Earth and Mars systems. The value labeled "Mars system (near Phobos)" is the value that is important for escaping from Phobos to interplanetary targets. Since the Phobos value is much smaller than the escape energies from the Earth surface, Mars surface, and even the Lunar surface, it will take the least delta V to escape from Phobos. Thus, as will be illustrated in Section 3.2, it is more efficient to refuel for planetary missions at Phobos than from a LEOSS (Low Earth Orbit Space Station, LMOSS (Low Mars Orbit Space Station), or a Lunar base.

TABLE 3.1 - Gravity Wells in Earth and Mars Systems

LOCATION	(ESCAPE VELOCITY**)^2 (KM/SEC)^2
EARTH SURFACE	100
MARS SURFACE	50
LUNAR SURFACE	10
MARS SYSTEM (NEAR PHOBOS)	1

* CASE FOR MARS II, "Phobos and Diemos as Resource and Exploration Centers"
** Approximate values from a chart

3.2 TRANSPORTATION NODE

Phobos would be a good transportation node and supply base because it has many resources and is very accessible from both inner planets and outer planets due to the small gravity well. This section compares the delta Vs starting from Phobos to the delta Vs starting from other possible starting sites.

3.2.1 COMPUTATION ASSUMPTIONS

Table 3.2 outlines the delta Vs that were computed from possible origins to possible customer and exploration sites. The delta Vs starting from all the planets were computed assuming the vehicle start from a 160 Nmi altitude, circular orbit about the planet. Similarly, the delta Vs going to all planets were computed assuming the vehicle finishes in a 160 Nmi. altitude, circular orbit about the planet. The delta Vs for a LEOSS assumed that it was in a 250 Nmi altitude, circular orbit. The delta Vs for an LMOSS were computed assuming the LMOSS was in a circular orbit with an altitude to planet radius ratio equal to the altitude to planet radius ratio for a LEOSS in a 250 Nmi altitude, circular orbit.

The interplanetary delta V values in Table 3.2 were calculated from a patched conic analysis. The patched conic program used to make the calculations and the generated output is listed among the sample calculations in Appendix A. The analysis used assumed that all the bodies were coplanar, point masses in circular orbits. In addition, all transfers were 180°.

The delta V values in Table 3.2 that involve orbit transfers about one planet were computed using a generic Hohmann transfer analysis. The orbits were assumed to be circular and coplanar, and the bodies were assumed to be point masses. The Hohmann transfer program used to generate this data is listed among the sample calculations in Appendix A.

3.2.2 SUPPLY BASE

Table 3.2 shows Phobos has relatively small delta Vs compared to the other possible origins. It does take more delta V to go from Phobos to a LEOSS than from a Lunar base to a LEOSS. Phobos can still be a good supply source for both a LEOSS and a Lunar Base because there is very little hydrogen on the Moon. In addition, Phobos could be a back up supply source of water, hydrogen, and oxygen for a LEOSS and Lunar Base if the Lunar Base production facilities were closed down for some reason.

3.2.3 EXPLORATION BASE

Brian O'Leary, who is one of the foremost scientists supporting the Mars colonization effort, says "that Phobos is currently the most accessible known natural object in the solar system." (Ref. 3.2) Accessibility is a key asset for a transportation node. The delta V comparison matrix, Table 3.2, supports this idea of accessibility since it shows that the exploration delta Vs from Phobos to exploration sites are smaller than most of the other possible supply bases. The delta Vs to outer planets which appear slightly more efficient than the Phobos delta Vs are those from a LMOSS and those from a Mars orbit. However, these delta Vs are only slightly more efficient. This is because it is more efficient to do a delta V in a lower orbit than a higher orbit due to the net change in energy. The same delta V will increase energy more if added to a large velocity (low orbit) than if added to a small velocity (high orbit). However, a vehicle starting from either of the LMOSS or Mars orbits must be supplied from Phobos or the Martian surface, so the net delta Vs of the LMOSS and Mars orbit are not as small as indicated by Table 3.2. Therefore, Phobos does have the smallest transfer delta Vs compared to the other possible supply bases. This is illustrated in section 3.3.

Phobos also has a natural advantage over Earth vicinity bases and space stations because Phobos is so much closer to the outer planets. The closer the base is to the exploration site the easier control of operation will be, the more reliable communications will be, and the larger exploration vehicles can be due to refueling capability.

From Table 3.2 it may be noted that less delta V is needed to go to Saturn than to Jupiter. This is a result of the fixed 160 Nmi. target altitudes about the planets and the much larger gravitational attraction of Jupiter. (For Jupiter it is difficult to define the surface, so operations may not be possible at that low altitude. Planetary data was obtained from ref. 3.3.)

3.3 PHOBOS EFFICIENCY

Table 3.3 shows the delta Vs for different transportation scenarios. These scenarios illustrate the combined results of Phobos' low gravity well and small delta Vs. The delta Vs are from places that have or may have the facilities to initiate a supply or exploration mission. The table shows that Phobos, with two exceptions, is the most efficient place to base missions of all types. The Lunar Base still has the lowest delta V to a LEOSS, and the Mars surface has a lower delta V to an LMOSS. However, these differences are very small and may be negligible depending on what supplies are needed and how available they are on the Moon and Mars. The calculations were made by adding a gravity well delta V term to the delta Vs in Table 3.2. The computations for Table 3.3 are in Appendix A.

TABLE 3.2 - VELOCITY MATRIX

POSSIBLE PLACES OF ORIGIN	POSSIBLE DESTINATIONS (km/sec)								
	SUPPLY SITES					EXPLORATION SITES			
	PHOBOS	LUNAR BASE	LEOSS	MARS	LMOSS	JUPITER	SATURN	URANUS	NEPTUNE
PHOBOS	——	4.14	5.44	1.34	1.27	22.05	16.65	13.95	15.02
LUNAR BASE	4.14	——	3.89	4.39	4.37	25.59	20.15	17.32	18.29
LEOSS	5.44	3.89	——	5.69	5.67	23.98	18.06	14.94	15.82
MARS	1.34	4.39	5.69	——	0.08	21.76	16.17	13.37	14.40
LMOSS	1.27	4.37	5.67	0.08	——	21.77	16.19	13.40	14.43

Table 3.3 - Supply Velocity Matrix

POSSIBLE ORIGINS	DESTINATIONS (km/sec)						
	LUNAR BASE	LEOSS	LMOSS	JUPITER	SATURN	URANUS	NEPTUNE
PHOBOS	4.14	5.44	1.27	22.05	16.65	13.95	15.02
EARTH SURFACE	13.03	9.14	14.81	33.12	27.30	24.38	24.96
MARS SURFACE	5.68	6.68	1.07	22.75	17.16	14.36	15.36
MOON SURFACE	——	4.02	4.50	25.72	20.28	17.45	16.42

3.4 PROXIMITY ACCELERATIONS

Proximity accelerations will directly effect the types and modes of transportation which are practical on the Phobos surface. Accelerations were calculated using both a three-body analysis and a two-body analysis.

3.4.1 THREE-BODY ANALYSIS

The three-body analysis was used to determine accelerations at the Phobos surface and at points up to 10 km. altitude above the surface model. The accelerations on the surface of Phobos were generated using a point mass within an ellipsoid surface model, Fig. 3.1, to compute radial distances from the center of mass of Phobos. Mars and Phobos were the primary bodies considered, and they were assumed to be point masses. The orbit of Phobos about Mars was assumed to be circular.

3.4.1.1 Surface Acceleration

The surface acceleration vectors were generated in the Phobos centered coordinate system illustrated in Fig. 3.1. In each of the planes illustrated in Fig. 3.2, points on the ellipsoid surface were chosen. At each point chosen, the position vector from the point to the center of Phobos was computed, and the acceleration vectors relative to the Phobos coordinate system were computed. The acceleration program used to generate this data may be found listed with the sample calculations in Appendix A. The program's output is listed after the program in the Appendix and consists of the resulting position vectors, acceleration vectors, and acceleration vector magnitude.

3.4.1.2 Normal and Tangential Acceleration Components

The normal and tangential accelerations at altitudes above the Phobos surface were computed along each of the axes defined in Fig. 3.1. Fig 3.3. is a plot of the magnitude of the normal acceleration component towards the center of phobos versus altitude above the ellipsoid surface model. Positive acceleration is toward the center of Phobos, and negative acceleration is away from the center of Phobos. The acceleration components for the Plus-Y, Minus-Y, Plus-Z, and Minus-Z axes are all the same for the three body solution as shown in Fig. 3.3. The Plus-X and Minus-X acceleration components for the three body solution are slightly different, but due to the resolution of the plot they appear the same. Fig. 3.4 is plot of the tangential accelerations versus radial distance. The Plus-Y, Minus-y, Plus-Z, and Minus-Z are on the same line. The tangential acceleration along the X-axis is zero. The program used to generate this data and the resulting output may be found listed with the sample calculations in Appendix A. The resulting output consists of the position vectors, the acceleration vectors, the magnitude of the acceleration vector, and the normal and tangential acceleration components with respect to Phobos.

3.4.1.3 Escape Velocity

The escape velocity of Stickney Crater was calculated using the computed normal acceleration at 13.5 km. radius on the plus-X-axis from the three-body solution. From this acceleration, an equivalent gravitational constant for Phobos was derived. This equivalent gravitational constant was then used to calculate the escape velocity to be 9.8407 m/sec. The two-body escape velocity using the actual mass of Phobos from Table 2.1 was calculated to be 9.8421 m/sec. This difference shows that Mars does have a small effect on escape velocity. The escape velocity calculations are listed in Appendix A.

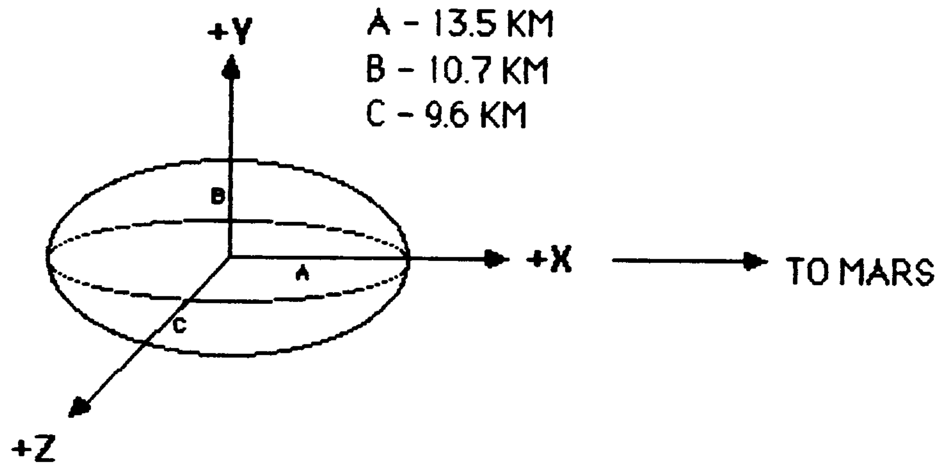


FIGURE 3.1 - Coordinate System for Ellipsoid Surface Model

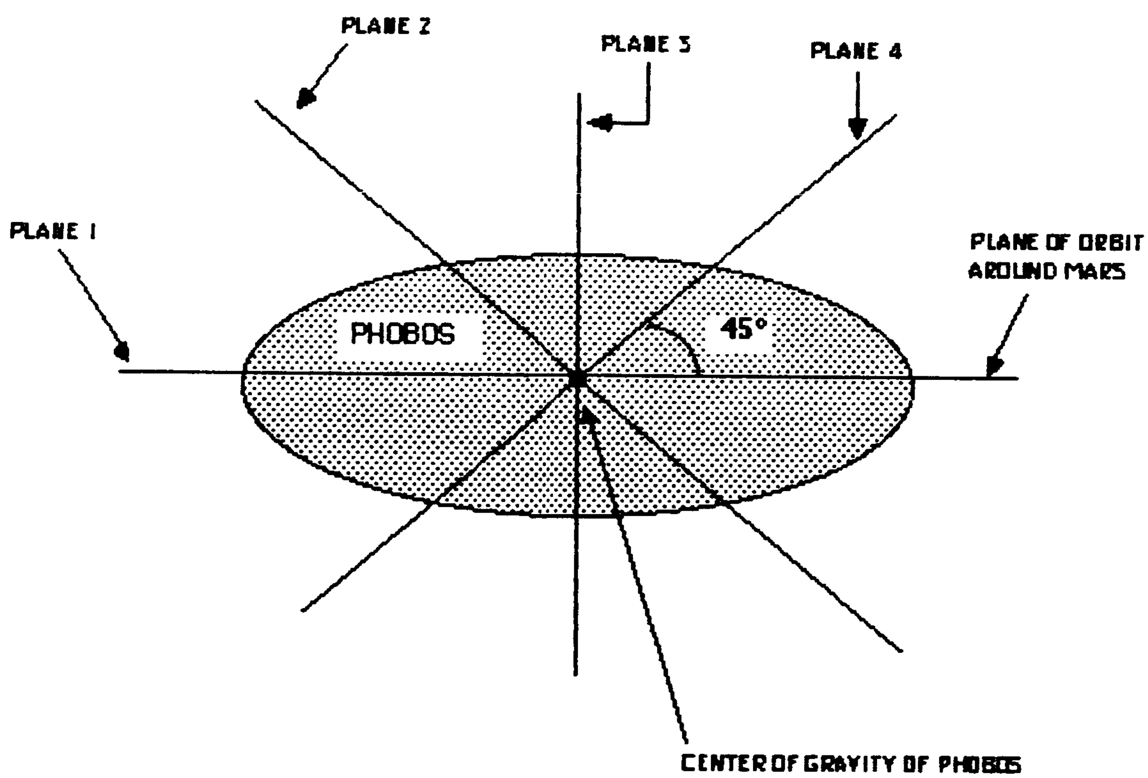


FIGURE 3.2 - Acceleration Gradient Planes

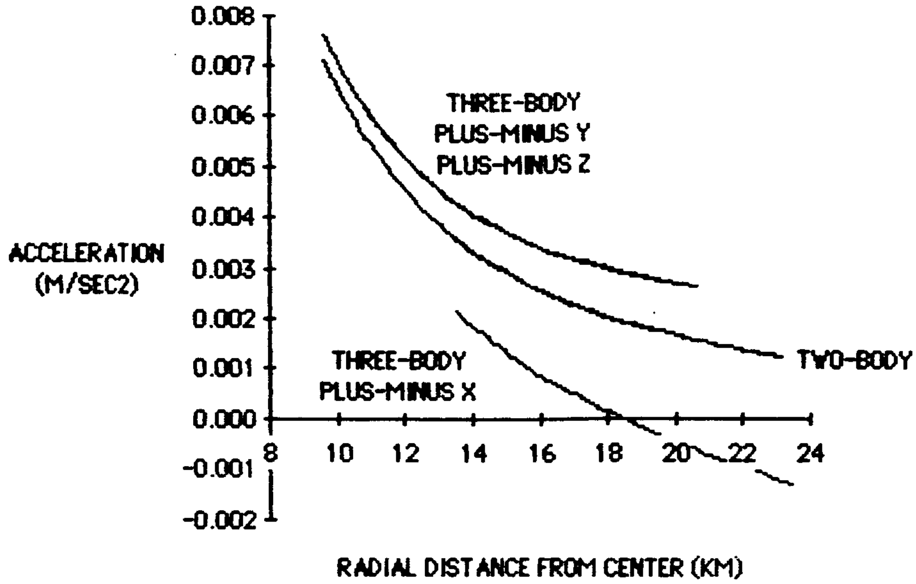


FIGURE 3.3 - Normal Acceleration Versus Radial Distance

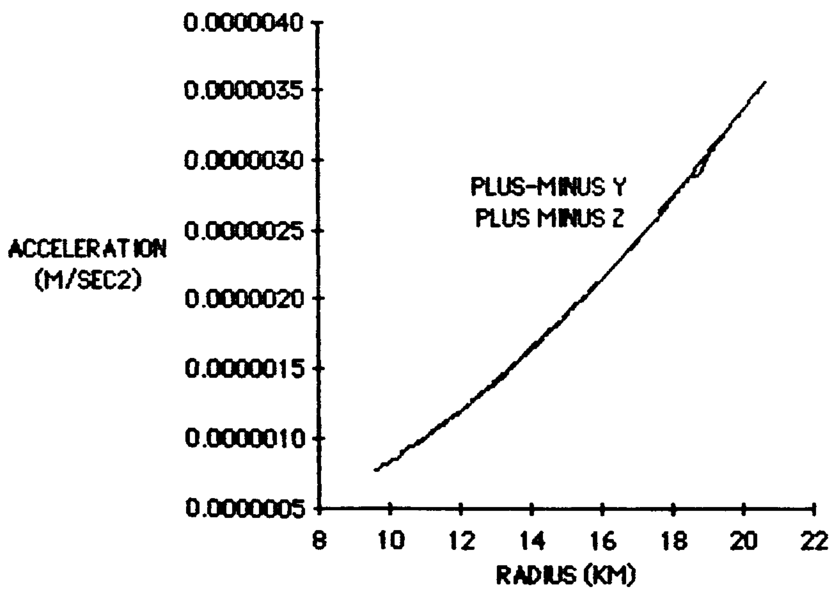


FIGURE 3.4 - Tangential Acceleration Versus Radial Distance

3.4.2 TWO-BODY ANALYSIS

The two-body problem was studied with Phobos as the primary body. This analysis computed the accelerations at different radii. The radius ranged from the smallest radius on the surface ellipsoid model (9.6 km) to 10km above the largest radius model (23.5 km). Fig. 3.3 includes a plot of the magnitude of the two-body acceleration component towards the center of phobos versus radius. The two-body program and resulting output may be found in Appendix A. The output consists of the position vector and the magnitude of the acceleration vector.

3.4.3 TWO-BODY AND THREE-BODY COMPARISON

The comparison of the two-body solution and the three-body solution shows that Mars has a definite effect on Phobos accelerations. Fig. 3.3 shows that in the three-body solution Mars not only decreases the normal acceleration component but also reverses the acceleration vector away from Phobos at about 18.5 km radius along the X-axis. The two-body solution is always positive and approaches zero as radius increases.

In the Plus-X direction (towards Mars) two factors cause the change in direction of the acceleration vector. One factor is the gravitational pull of Mars itself. The other factor is centripetal acceleration. The only point on the X-axis that is moving at the circular velocity for its radius from Mars is the origin of the coordinate system at the center of Phobos. On the Plus-X axis, the points are moving slower than circular velocity about Mars at their respective radius from Mars, so the points tend to drop towards Mars (away from Phobos).

In the Minus-X direction (away from Mars), only the centripetal acceleration causes the acceleration vector to change directions. Points on the Minus-X axis are moving faster than circular velocity about Mars, so the points tend to travel away from Mars (away from Phobos).

The gravitational pull of Mars can be positive or negative with respect to Phobos depending on which side of the X-axis the point of concern is on. This causes the accelerations to vary with radial distance along the X-axis. These differences are too small to be seen on Fig. 3.3, but the differences may be seen in the output listed in Appendix A following the three-body axes program.

The other difference that Mars' gravitational field makes is the tangential acceleration component. The two body solution only indicates a normal acceleration vector directed at the center of Phobos. The three-body solution shows that there is a tangential acceleration component except along the X-axis. This tangential component is very small, about 700 times smaller than the normal component at the greatest radius solved for.

3.5 FUEL REQUIREMENTS

The amount of fuel per trip was determined for each transfer delta V in Table 3.4. These fuel usage estimates were used to make sure that the production rate requirements set by the production and mining groups were realistic.

The vehicle payload mass for supply missions was estimated to be 200,000 Kg., and the vehicle payload mass for exploration missions was estimated to be 1,000 Kg. The two delta V programs in Appendix A, include a specific impulse algorithm that computes how much liquid hydrogen and liquid oxygen that each delta V will require for the respective vehicle mass (I_{sp}=360 sec for liquid hydrogen and liquid oxygen). The results of the fuel usage computations are presented in Table 3.4. The program output is listed with the delta Vs following the program. The algorithm and I_{sp} value were obtained from Ref. 3.4.

The amount of fuel per year required to fulfill all the missions listed in Section 1.5.6 is 2154 mt which is less than the projected yearly production of 5402 mt/year. This projected production was obtained using an oxidizer to fuel ratio of 7, from Ref. 4, and the production estimates from Table 2.4. The calculations are listed in Appendix A.

3.6 WEAKNESSES OF ANALYSIS - POINT MASSES

All computations assumed that the orbiting bodies were point masses. The error incurred by this assumption is negligible for the orbital transfer calculations.

The error incurred for the gravity gradient calculations are small, but may not be negligible. Phobos is a very asymmetrical body. The computations for the surface accelerations included only the part of the gravity gradient due to the variation of radial distance from the center of mass by using an ellipsoid surface model. The part of the gravity gradient due to the non-homogeneous, non-spherical mass distribution of Phobos was not taken into account. This small error should not greatly affect the relative magnitudes of the calculated values.

TABLE 3.4 - FUEL USAGE MATRIX

POSSIBLE PLACES OF ORIGIN	POSSIBLE DESTINATIONS (kg x 10^5)								
	SUPPLY SITES (200,000 kg Payload)					EXPLORATION SITES (1000 kg Payload)			
	PHOBOS	LUNAR BASE	LEOSS	MARS	LMOSS	JUPITER	SATURN	URANUS	NEPTUNE
PHOBOS	——	4.47	7.34	0.92	0.87	5.15	1.11	0.51	0.70
LUNAR BASE	4.47	——	4.03	4.94	4.90	14.03	3.00	1.34	1.77
LEOSS	7.34	4.03	——	8.02	7.96	8.91	1.65	0.68	0.87
MARS	0.92	4.94	8.02	——	0.05	4.74	0.97	0.43	0.58
LMOSS	0.87	4.90	7.96	0.05	——	4.75	0.97	0.43	0.59

4.0 MACROSCOPIC BASE CONFIGURATION

The previous sections outline the benefits and production goals of an industrial Phobos base. This section will describe the layout of the base on the surface of Phobos and some of the subsystems required to deploy the base on the Phobos surface.

4.1 GENERAL CONCEPT

The Phobos base will consist of a collection of specific application modules (habitat, processing, power, mining, storage, etc.), mounted within standardized system modules (simple truss frameworks). For on-orbit maneuvers the Phobos base will be configured in a tower formation. Once on the Phobos surface, the base will unfold in a "tackle box" fashion, one module at a time. Figure 4.1 illustrates the tower configuration and the "tackle box" deployment concept for a two system module configuration. The following sections will discuss design requirements for a base configuration involving multiple system modules.

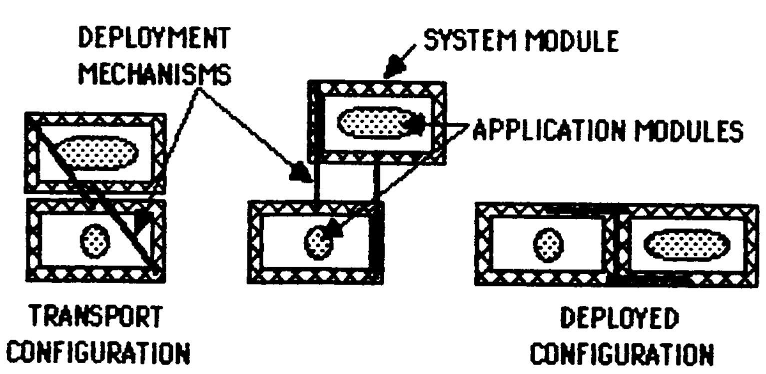


FIGURE 4.1 - General Concept for Phobos Base Configuration

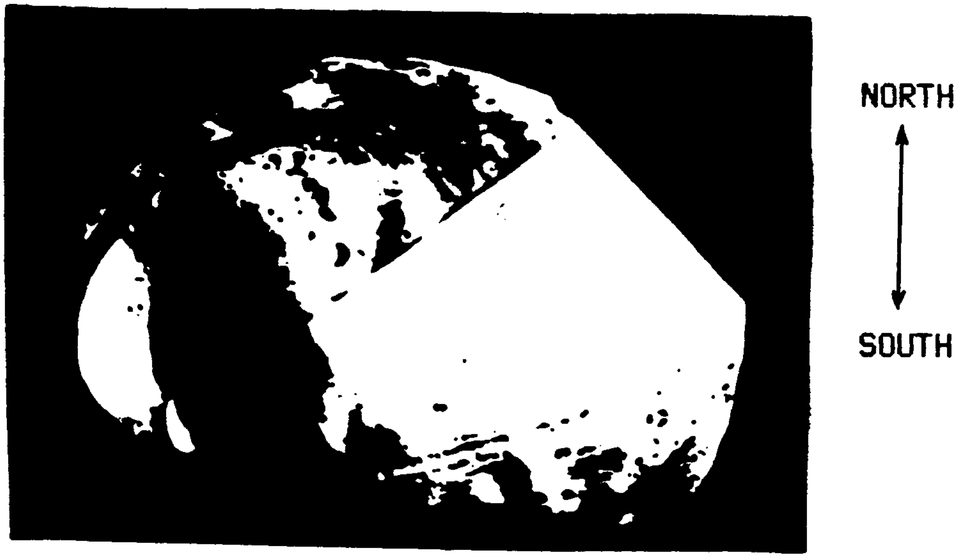
4.2 LANDING SITES

Phobos landing sites were researched by the Spring 1986 UT design team -- Texas Space Systems (TSS)[1]. TSS designated Stickney crater as the primary landing site and several of the trenches emanating from Stickney as secondary landing sites. Figure 4.2 defines the orientation of Stickney Crater with respect to Phobos and Mars (Stickney always faces Mars). Stickney crater has several advantages over other possible landing sites: natural radiation protection, surface conditions conducive to anchor and mining systems, and continuous observation of Mars. Table 4.1 presents the decision matrix used to designate Stickney crater as the primary landing site for a Phobos base; the remainder of this section will discuss the requirements listed in Table 4.1.

TABLE 4.1 - Phobos Landing Site Decision Matrix

REQUIREMENT / OPTION	TRENCH	CRATER EDGE	CRATER CENTER	OTHER LOCAL
RADIATION PROTECTION	3	1	2	4
ANCHOR SYSTEM	1	1	2	3
MINING SYSTEM	2	1	1	3
EXPANSION	3	2	1	2
MARS OBSERVATION	2	1	1	2

1 = BEST OPTION 3 = WORST OPTION



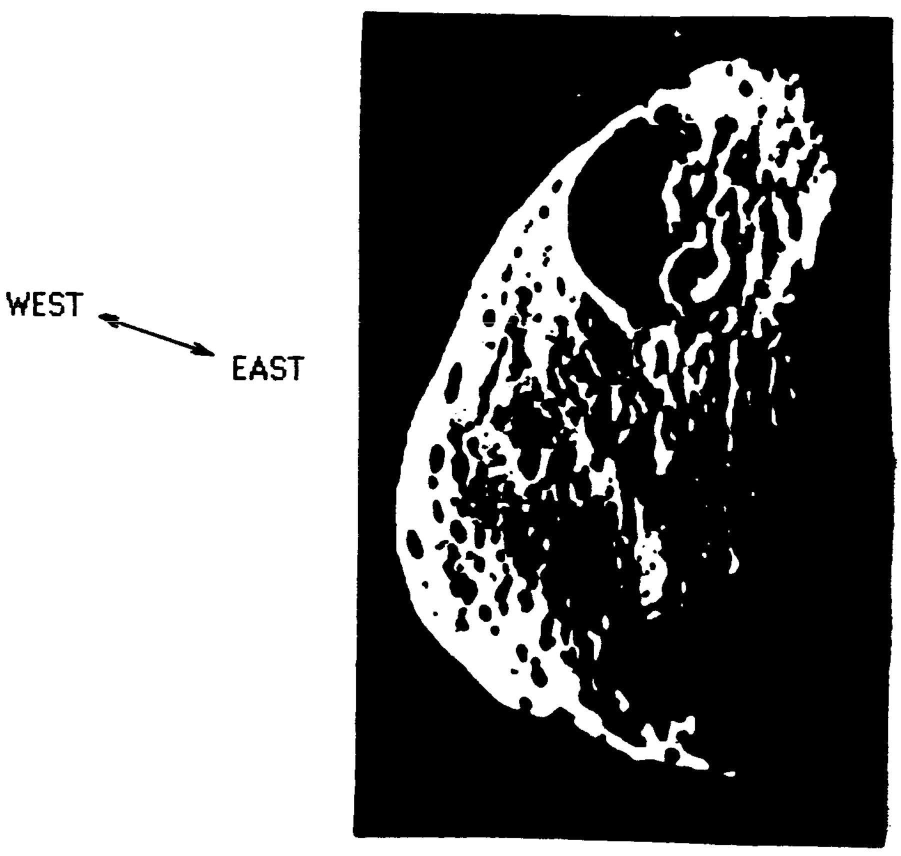


FIGURE 4.2 - Orientation of Stickney Crater[2]

Radiation protection -- since Stickney crater is always directly facing Mars, the interior of the crater is shielded from radiation when Phobos is between Mars and the Sun, when Mars is between Phobos and the Sun, and when the rim of the crater shades the crater's interior. Figure 4.3 illustrates a simple daytime / nighttime pattern for Stickney crater. The daytime / nighttime analysis presented in Appendix A of this report estimates the time of solar exposure for Stickney crater to be approximately 42.5 of Phobos' orbital period about Mars (worst case).

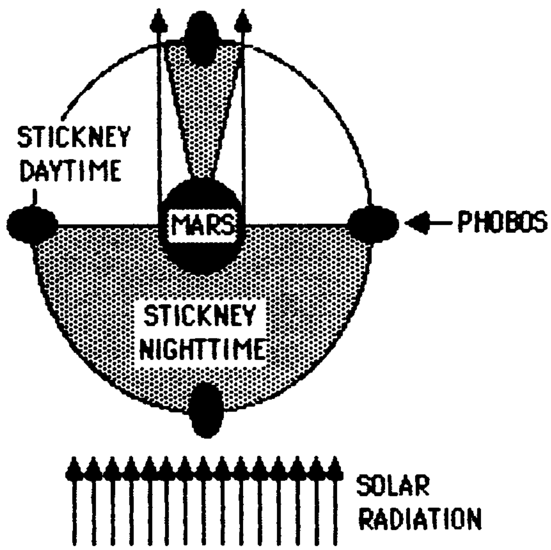


FIGURE 4.3 - Stickney Crater Daytime / Nighttime Intervals

The loose regolith thought to be covering the floor of Stickney crater would also provide excellent radiation protection. A previous study conducted by a NASA/UT summer intern design team estimated a worst case radiation exposure for a free space environment about Mars as 10 REMS/year with 110 grams/cm^3 shielding[3]. This exposure rate was based on energy flux of the following magnitudes: 10% at 10^{20} MeV (solar proton events) and 90% at 10^3 MeV (background radiation). Based on 42.5% daytime (42.5% of 10 REMS/year @ 110 g/cm^3) and a regolith density of 1.5 g/cm^3, 0.75 meters of Phobos regolith will allow 4.25 REMS/year radiation exposure -- worst case. This radiation exposure satisfies the 5 REMS/year allowable exposure for radiation workers[4]. Regolith depth for total radiation shielding may be calculated using a method[5] presented in Appendix A. This method yields total shielding requirements of 2.23 meters regolith for 10^3 MeV energy flux and 171.6 meters regolith for 10^{20} MeV energy fluxes. Regolith depth requirements for a Phobos base safe haven will be discussed further in Section 4.4.

Surface conditions -- base anchoring systems and surface mining systems present special problems in the milli-g environment of Phobos: how to supply the reaction forces necessary to initially anchor the base and how to break up the surface of Phobos into manageable portions for processing. The solutions to these problems, presented in Sections 4.3.3 and 5.0 respectively, are simplified when the Phobos surface consists of loose regolith instead of solid rock. Regolith depths in Stickney crater are estimated to be 10 meters at the crater's edge and over 200 meters at the crater's center[6]; trenches emanating from Stickney may contain as much as 20 meters of regolith.

Stickney also provides adequate space for expanding mining operations which may proceed in all directions from the base. However, trench mining operations are limited to unidirectional expansion which lengthens supply lines and creates a greater chance for single point failures. The more regolith within

Stickney, the more options available for anchoring, mining, shielding, etc..

Mars observation -- because Stickney crater is always facing Mars, Stickney is the logical location for a Mars observation facility. Planetary surveys of Mars and communication links to Earth or other space settlements can both be accomplished by a base within Stickney.

4.3 SYSTEM MODULE DEFINITION

The Phobos base system module, SM, is a framework of truss elements which will standardize the interfacing of the Phobos base. The SM may be envisioned as a tray of a fisherman's tackle box; the tray is generic enough to hold any type of specialized components (lures, bait, weights, line, etc.) a fisherman needs to complete his fishing adventure. The basic geometry of the SM is constrained by several design factors. Table 4.2 presents a comparison of three SM geometries -- square, hexagon and octagon -- for each of seven design factors. Based on the decision matrix of Table 4.2, the octagon prevailed as the best of the three SM geometries for a Phobos application. The remaining portions of this section will discuss the design requirements of Table 4.2.

Modularity -- The SM must be a rigid standard; one SM fits all (figuratively speaking). The SMs must be able to interface at geometrically similar faces. For an octagon, this modularity means one SM may be stacked on another SM eight different ways; or two SMs side by side may be positioned in 64 different orientations. Figure 4.4 presents the baseline SM geometry and size. The internal dimensions of the SM were based on maximum Shuttle cargo lengths.

TABLE 4.2 - System Module Geometry Decision Matrix

REQUIREMENT \ OPTION	SQUARE	HEXAGON	OCTAGON
MODULARITY	1	1	1
APPLICATION MODULE VERSATILITY	2	1	1
DEPLOYMENT CONFIGURATION VERSATILITY	2	3	1
DEPLOYMENT SYSTEM PLACEMENT	1	3	2
ANCHOR SYSTEM PLACEMENT	1	1	2
SIMPLICITY	1	3	2
WEIGHT	1	3	2

1 = BEST OPTION 3 = WORST OPTION

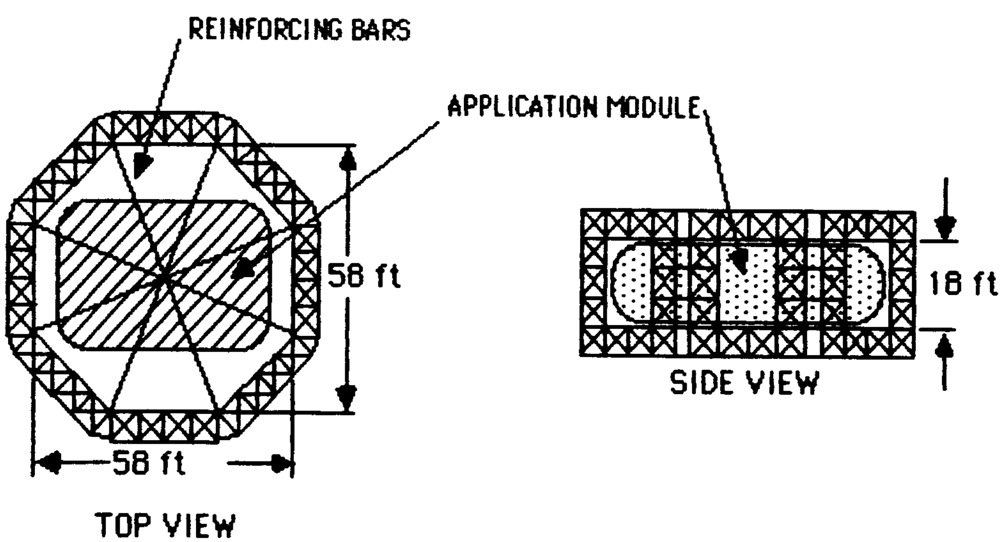


FIGURE 4.4 - Baseline System Module Geometry

Application module versatility -- an application module, AM, is a module housed within a SM and dedicated to a specific purpose; i.e. life support, materials processing, power generation, storage, etc.. The shape of an AM should not be restricted to a standardized, rigid definition -- that is the role of the SM. The AM must conform to SM (or group of SMs) volume and mass limitations, but the shape of the AM should depend only on its application; clearly, a habitat module will have a different geometry than a power plant. Among the three SM geometries, the octagon delivers the best enclosed area to perimeter distance ratio; in other words, the octagon possesses the most useful area for AM placement. This useful area result may be explained by comparing a circle (a polygon with an infinite number of sides) and a square which enclose unity areas, see Figure 4.5.

$A = 1 = \pi r^2 \Rightarrow r = 0.564$
$P = 2\pi r$
$A/P = r/2 = 0.282$

$A = 1 = S^2 \Rightarrow S = 1$
$P = 4S$
$A/P = S/4 = 0.25$

$0.282 > 0.25$

FIGURE 4.5 - System Module Useful Area Comparison

Deployment configuration versatility -- for base operations reasons (AM interfaces, storage access, etc.) and obstacle avoidance reasons (during deployment), the Phobos base must have the capability of multi-directional deployment. The octagon provides the best deployment versatility of the three SM geometries because of its eight faces. Figure 4.6 shows two possible surface configurations using octagon SMs.

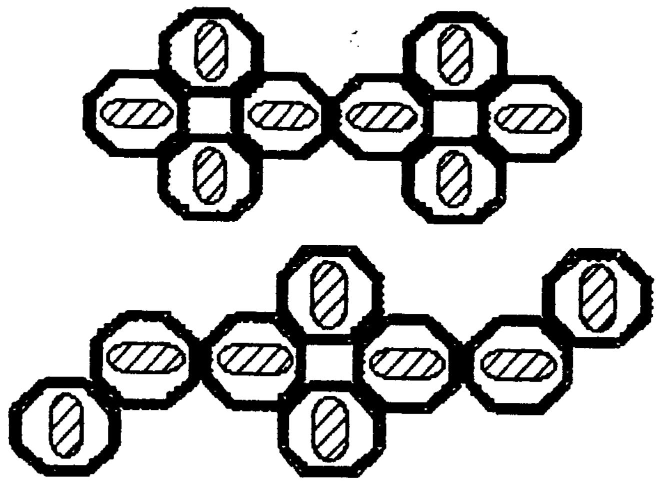


FIGURE 4.6 - Possible Surface Deployment Configurations

Deployment system placement -- The deployment system, discussed in detail in Section 4.3.4, consists of two eletrically powered lever arms mounted on each of two directly opposing faces of the SM. The square SM provides the best placement of the deployment system among the three SM geometries because of the square's larger faces. For the hexagon SM, deploying face to face would require mounting the lever arms at the corners of the SM -- adding unnecessary complexity to the design.

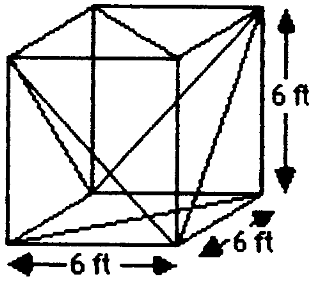
Anchor system placement -- the anchor system, discussed in detail in Section 4.3.3 should be positioned in the interior of the SM to preserve exterior SM modularity. The best position for the anchor systems lies in the corners of the SM where the most "wasted space" resides. The square SM supplies the most corner space of the three SM geometries; the hexagon supplies a smaller amount of corner space and the octagon an even smaller area.

Simplicity -- of the three SM geometries, the square SM yields the most simplistic designs in terms of truss structures, deployment systems anchor systems and SM interfacing. However, the octagon yields only slightly more complex designs because the additional four faces. The hexagon SM design involves severe complexity because the SMs cannot be deployed face to face with out intricate machinations.

Weight -- the octagon SM geometry has a shorter perimeter distance, but 12 more supporting columns than does the square SM geometry -- a similar analogy may be applied to hexagon and square SM geometries. Therefore, of the three SM geometries, the square SM will possess the least structural mass and the hexagon SM the most structural mass because of deployment and interfacing complexities.

4.3.1 TRUSS ELEMENT DEFINITION

Truss elements comprising the framework of the SM are based on current space station truss designs[7]. Figure 4.7 presents the baseline SM truss element; this element represents a highly redundant system which provides torsional, bending and axial stiffness on all axis. The overall sizes of the truss elements and the individual bars will have to be re-evaluated because of potentially high loading conditions on the truss elements during on-orbit maneuvers. Structural integrity analysis for the truss elements and the SMs is beyond the scope of the current Phobos base design project, but such analysis should be conducted in the future. Truss materials should also be reviewed; Table 4.3 presents a decision matrix for truss element materials based on material properties. In all cases (except radiation protection because of low density), the graphite/epoxy composites show clear superiority to aluminum, titanium and steel alloys[8]. However, this decision does not include an important factor -- cost. Although the material costs have not been researched for this report, material costs will be minor compared to other mission costs -- transportation, man-hours, insurance, etc.



- REDUNDANT
- TORSIONAL STIFFNESS
- BENDING STIFFNESS
- AXIAL STIFFNESS

FIGURE 4.7 - Baseline System Module Truss Element

TABLE 4.3 - Truss Materials Decision Matrix

REQUIREMENT \ OPTION	ALUMINUM	TITANIUM	STEEL	GRAPHITE/EPOXY
STIFFNESS	4	3	2	1
STRENGTH	4	3	2	1
HEAT EXPANSION	4	2	3	1
WEIGHT	2	3	4	1
OUTGASSING	1	N/A	N/A	1
RADIATION PROTECTION	3	2	1	4

1 = BEST OPTION 4 = WORST OPTION

4.3.2 APPLICATION MODULE MOUNTING SYSTEM

Two practical design philosophies exist for methods of mounting an AM within a SM: additional truss structures and high tensile nets. Both mounting systems will require custom construction for each AM because of each AM's unique shape. Additional truss structures will require reinforcement of the AM at the high stress contact points and throughout the AM to prevent buckling. Conversely, high tensile nets will require minimal AM reinforcement because the nets will be designed to distribute the supporting load uniformly over the surface of the AM. High tensile nets with supporting straps will allow the AM to be repositioned within the SM for center of gravity alignment (for on-orbit maneuvers) and AM interfacing (for surface deployment). Custom high tensile nets will also be easier to manufacture than custom truss structures and will conceivably possess less structural mass than a truss system. Figure 4.8 illustrates a high tensile net AM mounting system and Table 4.4 presents the AM mounting system decision matrix.

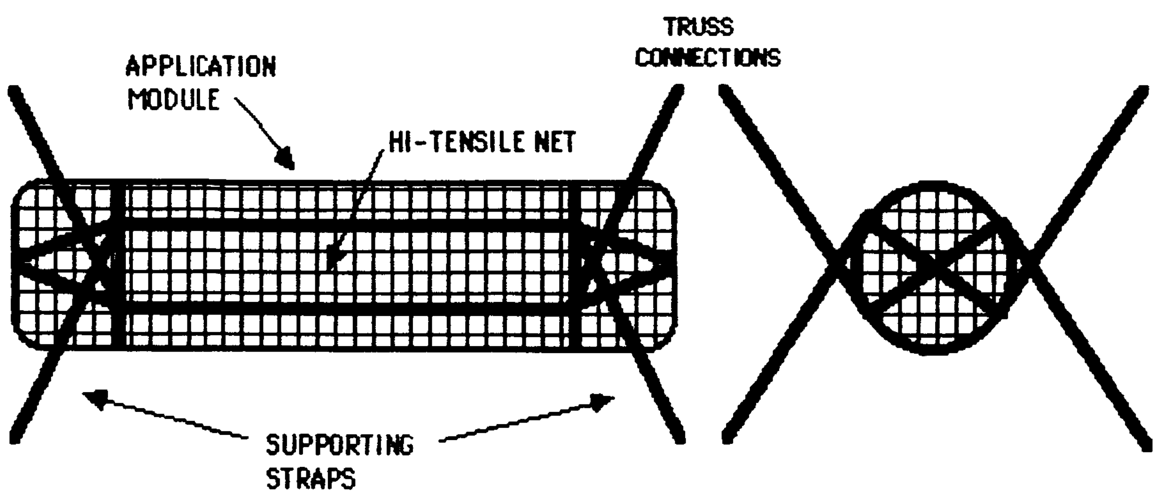


FIGURE 4.8 - High Tensile Net Application Module Mounting System

TABLE 4.4 - Application Module Mounting System Decision Matrix

REQUIREMENT \ OPTION	TRUSS STRUCTURES	HI-TENSILE NET
APLLICATION MODULE VERSATILITY	2	1
CENTER OF GRAVITY ADJUSTMENTS	2	1
WEIGHT	2	1
SIMPLICITY	2	1

1 = BEST OPTION   2 = WORST OPTION

Once the SM is anchored to the Phobos surface, the straps may be replaced or relieved with minimal bar supports. The main problem of a high tensile net mounting system will be creating enough stiffness to eliminate "slosh" effects on-orbit.

4.3.3 BASE ANCHOR SYSTEM

The Phobos base anchoring system must provide the following capabilities:

1) supply reaction forces necessary to penetrate the Phobos surface,
2) variable anchor depth,
3) soft or hard (regolith or rock) anchor medium,
4) retractable, and
5) simplistic.

Four types of anchors have been reviewed based on these requirements:

1) a conventional self tapping drill,

2) a self tapping drill with extending blades -- a reverse umbrella,

3) an inflatable subsurface structure, and

4) a surface freeze technique.

Section 4.3.3.1 presents the baseline Phobos base anchor system; Section 4.3.3.2 discusses the other anchor systems considered. Table 4.5 summarizes the ability of the four base anchor designs to meet the specified requirements.

TABLE 4.5 - Base Anchor System Decision Matrix

REQUIREMENT \ OPTION	REVERSE UMBRELLA	CONVENTIONAL DRILL	INFLATABLE STRUCTURE	SURFACE FREEZE
INITIAL SET ON CONTACT	1	1	1	1
SOFT & HARD SURFACES	1	1	3	3
VARIABLE DEPTH	1	1	4	3
RETRACTABLE	3	1	4	2
SIMPLICITY	3	1	4	2
POWER REQS	1	1	4	3

1 = BEST OPTION   4 = WORST OPTION

4.3.3.1 Baseline Anchor System

Table 4.5 reveals the conventional self tapping drill concept to be the best among the four base anchor concepts. Figure 4.9 presents a conceptual design of the self tapping drill anchor. The design incorporates several small diameter blades to provide the "self tapping" capability and one large diameter blade supply vertical anchor forces once the anchor is set.

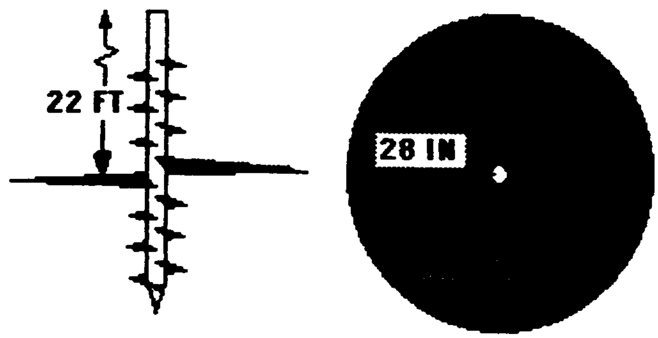


FIGURE 4.9 - Conventional Self Tapping Drill Anchor

The blades of the anchor are displaced from one another to reduce the possibility of rotating a "cylinder" of regolith instead of spiraling through the regolith. In the high vacuum, low gravity environment of Phobos, the regolith may possess fluidic properties, such as viscosity, too large to be neglected. If viscosity does become a factor, the small pitch of the anchor blades must be compensated by offsetting each blade a distance which will reduce the fluidic affects of the regolith. The pitch of the blades will be small (approximately 10 degrees) to insure the blades move through the regolith instead of displacing the regolith. One large blade is all that is necessary to provide a large surface area perpendicular to the vertical anchor forces. Preliminary analysis, presented in Appendix A of this report, suggests a blade pitch of 10° with a large blade diameter of 28 inches will provide an effective self tapping drill design in terms of power consumption and drilling downforce. Ideal power consumption was estimated to be 38 kW for a rotation rate of 30 rpm. In addition, the shaft of the drill may be hollow to allow power cables for a heated drill bit. A heated drill bit would give the anchor the capability of anchoring directly to rock by melting through the rock surface and then letting the rock cool around the anchor.

Each SM will have one to two sets of counter rotating anchors to supply a moment balance between the applied torques to the anchor shafts. Two anchors (one set) would be optimal in terms of power and simplicity, but for vertical stability during deployment (Section 4.4), the few initial SMs deployed may require two sets of anchors. Each SM will also have three adjustable strut systems to provide a leveling and lateral support capability for the SM. Fins attached to the surface pad of the strut system, will insert perpendicular to the Phobos surface during final anchoring procedures and provide the SM with lateral support. Figure 4.10 and 4.11 illustrate the implementation of the anchor system for each system module. This anchor system will fulfill the requirements listed in Table 4.5.

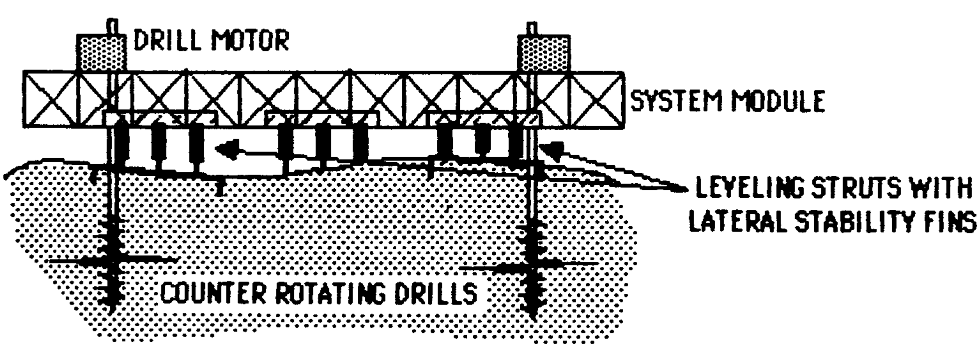


FIGURE 4.10 - Base Support Strut System

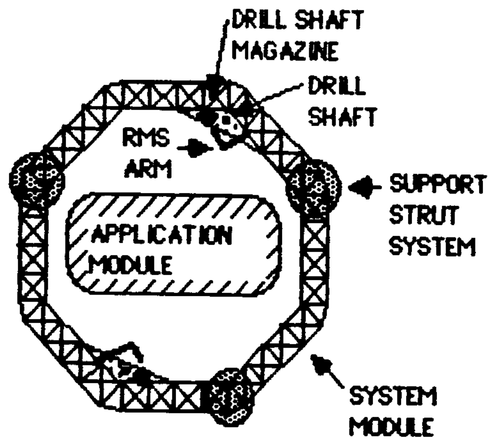


FIGURE 4.11 - Baseline Anchor and Support Strut Configuration

Initial set upon surface contact -- The inertia the base will have when "landing" on Phobos will supply a large downforce (impulse) with which the anchors will begin to drill themselves into the regolith. Once the base's inertia has been dissipated, the mass of the base will provide several hundred pounds of downforce to facilitate the drilling action of the anchors. If necessary, additional downforce may be supplied by the deployment system (Section 4.3.4) after the first SM has been securely anchored.

Soft and hard surfaces -- the self tapping drills may anchor in the loose regolith, or, with the addition of a heated bit, bore directly into rock.

Variable depth/retractability -- The nominal depth of the anchor (20 feet) may be extended by feeding additional drill shafts, stored in a rotary magazine, to the drill motor using the mobile remote manipulator system (MRMS) discussed in Section 6.0. However, anchor depth analysis presented in Appendix A of this report shows a 20 blade depth will supply approximately 1600 of vertical anchor force. Also, a DC motor will provide the anchor with a reversible and variable speed rotation, i.e., the anchor will drill itself out of the regolith just as easily as it drilled itself into the regolith. The reversible nature of the anchor system is not as important on the base as on the mining track system or the main mining stations (Section 5.0) which absolutely require a relocatible anchor capability.

Simplicity -- the conventional self tapping drill concept incorporates a single mechanical part, the drill itself (excluding the motor).

Power requirements -- although power requirements were not analyzed for the other three anchor concepts, displacing regolith would require much more power than simply passing through the regolith. In the later case, energy is required to overcome only the surface friction (ideal case), but displacing the regolith would require frictional energy as well as work energy to actually move the regolith.

4.3.3.2 Additional Anchor Options

The "reverse umbrella" anchor illustrated in Figure 4.12 is also a self-tapping drill design, but much more complex than the conventional drill design. The reverse umbrella anchor would be drilled to a certain depth, at which point the blades would be released at one end. Once the blades are unconstrained, the drill would be pulled towards the surface; this motion would cause the blades to fold down and anchor the SM. The reverse umbrella system was eliminated from the final anchor system because of the system's additional complexity and poor retracting (once the blades are released) characteristics.

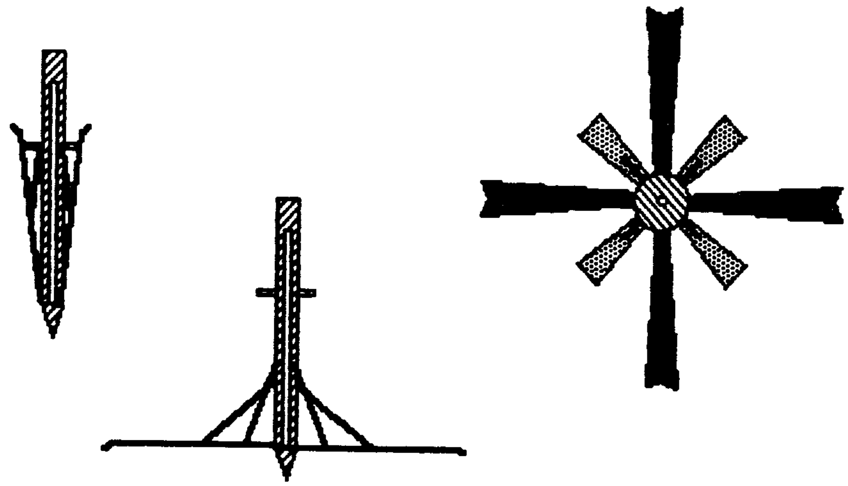


FIGURE 4.12 - Reverse Umbrella Anchor System

The two other anchor systems studied, inflatable structures and surfaces freezes, are of the same type and appear in Figure 4.13. Both systems require two anchoring stages: a preliminary anchor to supply the reaction forces necessary to place the primary anchor -- the second stage. The preliminary anchor used would be very similar to the conventional drill anchor discussed previously. The dual anchor nature of these two systems was the primary reason for eliminating them from the final anchor design.

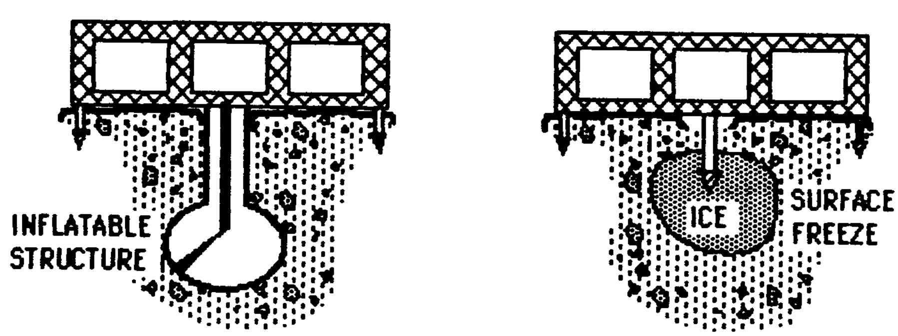


FIGURE 4.13 - Inflatable and Surface Freeze Anchor Systems

The inflatable structure would be deployed by inserting a tube containing the structure into the regolith and then inflating the structure. Once inflated, a stiffening agent would be sprayed on the interior of the structure to prevent collapsing. Power requirements would be excessive compared to the other anchor systems because of the amount of regolith displaced by the inflatable structure. Once the stiffening agent is applied, the structure could not be retracted without breaking the interior stiffner coating. Depth is also a restriction for an inflatable structure because of the increasing pressure resistance of the regolith with depth.

The surface freeze system involves injecting the regolith with water and allowing the water to freeze a block of regolith onto the injecting mechanism. This system presents a problem due to the low bearing strength of ice.

4.3.4 DEPLOYMENT SYSTEM

The baseline Phobos base deployment system consists of four linearly telescoping, crane type lever arms -- two arms on each of two directly opposing faces. Two arms on each face allow a SM rotating capability as seen in Figure 4.14. Figure 4.14 also illustrates the telescoping arms are necessary for SM clearance reasons. The ends of the deployment arms will be mounted to the SM via monocoque panels which will be position on the face of SM truss element in place of the standard bar. The electromagnetic torque motor for the lever arm will be mounted directly to the monocoque panel at one end of the lever arm; the other end of the lever arm will be a free pivot. In essence, only one set of four lever arms is necessary for base deployment -- the set will be relocated to different SMs in turn of their deployment. The actual power supply would be the only component of the deployment system that would not be transferable. The system would "plug" into the common base power supply at each SM. The lever arms would be repositioned using the same MRMS which was discussed as an aid to the anchor system.

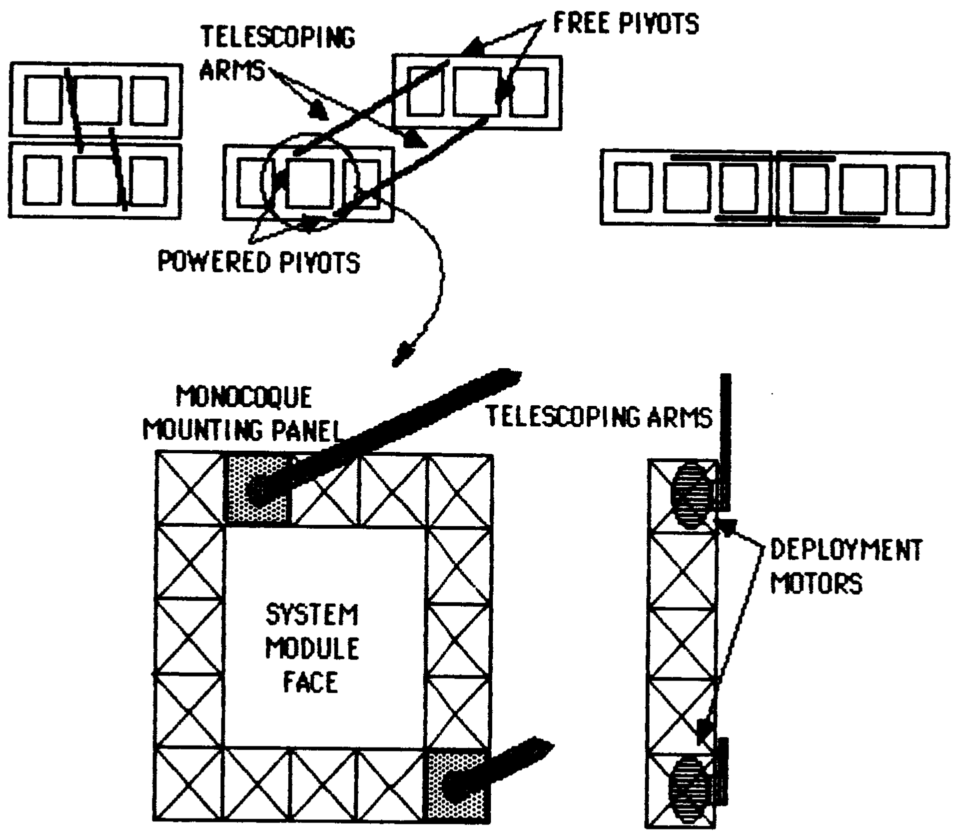


FIGURE 4.14 - System Module Deployment System

A single deployment arm which employed two lever arms with a powered joint was also considered, but compared to the telescoping arm, the relative complexity of the dual arm system in terms of geometry, power systems, and repositioning, eliminated the dual arm configuration from the baseline deployment system configuration.

4.4 BASE DEPLOYMENT SCENARIO

This section will present the baseline configuration of the Phobos industrial base as well as the Phobos base deployment sequence of events.

Figure 4.15 presents a conceptual view of the on-orbit tower configuration of the Phobos base. Figure 4.16 represents the current baseline configuration of the Phobos industrial base. The base will be positioned near the south wall of Stickney crater with radially expanding mining operations. The baseline configuration consists of seven system modules deployed in the order listed below:

1) deployment module,
2) safe haven/habitation module,
3) laboratories module,
4) storage/base vehicles module,
5) raw materials processing module,
6) mining module, and
7) primary power plant module.

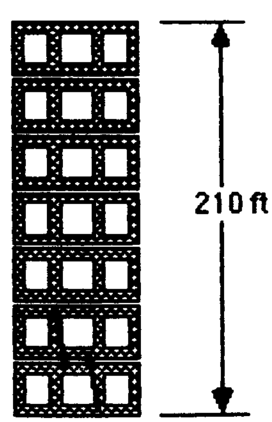


FIGURE 4.15 - On-Orbit Tower Configuration of Phobos Base

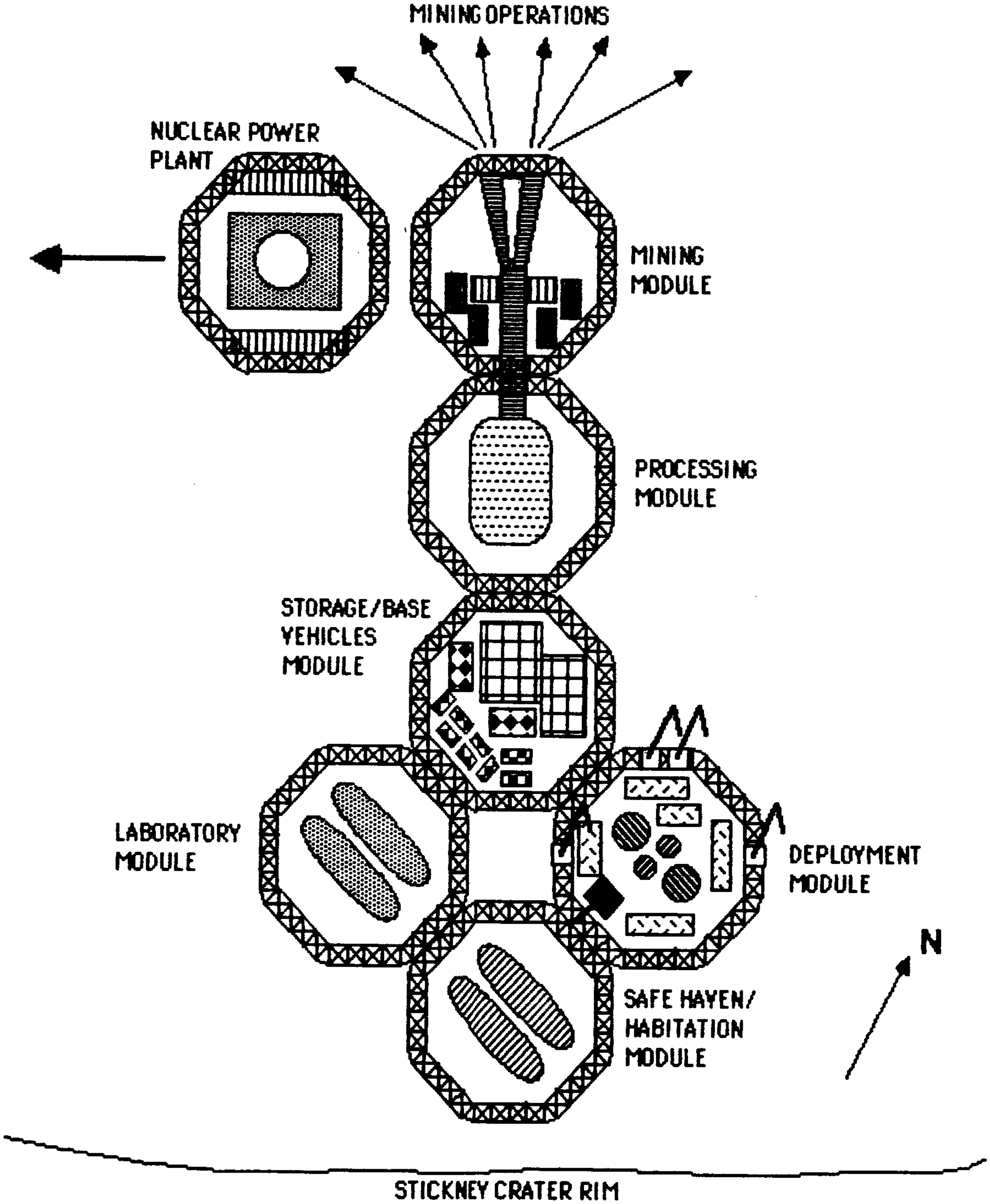


FIGURE 4.16 - Baseline Configuration for Phobos Base

4.4.1 DEPLOYMENT MODULE

The base will rendezvous with Phobos (at Stickney) in a tower configuration with the deployment module at the "bottom" and the primary power plant at the "top". The deployment module will contain all the tools and equipment required to deploy the Phobos base: initial power supply, MRMS systems, safe haven pit excavation equipment, etc.. The initial power supply will become the base's backup power system once the primary power plant is operational.

The tower configuration will approach the surface of Phobos with a slight velocity to provide the anchor system with a reaction (inertial) force with which the anchors may begin to drill into the regolith. Once the two drills have established the necessary depth to provide the specified anchoring forces, the strut systems will "level" the tower for the best deployment orientation -- the orientation of the deployment module, with respect to the Phobos surface, will dictate the orientations of the SMs to follow. The tower configuration will be stabilized during the entire initial anchor sequence by the on-orbit attitude control system -- The control system will merely dispatch an attitude control command once the proper tower orientation for anchoring has been established. However, due to the semi-proximity operations nature of the base rendezvous with Phobos, mission timing will be critical for a successful "landing".

When the deployment module has completed anchoring procedures, the safe haven pit excavation equipment will be deployed from the deployment module to excavate the safe haven pit before the safe haven/habitation module (SHHM) is deployed over its designated space. The MRMS systems will be initialized from the deployment module on the exterior of the deployment module concurrently with pit excavation. Also concurrently with pit excavation, the deployment module will be freed (SM interfacing disconnected) from the SHHM and other equipment will be unpacked: vehicle parking pads (discussed later), special SM interfacing tracks for MRMS transmodule movement, etc..

When the safe haven pit has reached a depth where approximately 8 feet of regolith (radiation shielding requirements from Section 4.2.1) may be placed on top of the save haven, the SHHM is ready to be deployed.

4.4.2 SAFE HAVEN/HABITATION MODULE

The SHHM contains two habitation modules, a safe haven and an every day habitat, as well as the access tubes and airlocks necessary to link the two habitation modules together after safe haven burial.

The entire tower configuration, from the SHHM to the primary power plant module, PPPM, will be slowly lifted from the deployment module with the lever arms of the deployment system. Care must be taken to not only clear the deployment module but also to align the two SMs before the SHHM's strut pads contact the Phobos surface -- repositioning may be difficult if the fins of the strut pads perform as designed. Alignment care must be taken for every SM deployed.

Once the SHHM is resting on the Phobos surface, the deployment arms can supply the reaction forces necessary to start the SHHM drill anchors. If required the struts of the SM will be adjusted to improve SM alignment. These actions will be duplicated for every SM deployed.

Once the SHHM is firmly anchored, the adjustable straps of the safe haven's AM mounting system may be used to lower the safe haven into its radiation shielding pit. The surface access systems will then be secured and the safe haven covered with regolith using the same equipment which initially moved the regolith.

During safe haven burial, the deployment system will be relocated to the laboratories module using the MRMSs and the the lab module will be disconnected from the SHHM. The deployment process then repeats for each SM in turn.

4.4.3 LABORATORY MODULE

The laboratory module will contain any and all scientific hardware and experimentation facilities suitable for Phobos applications. The laboratory module follows the SHHM in deployment sequence so that the habitation modules and laboratory modules have the capability to be rigidly connected with pressurized interfaces.

4.4.4 STORAGE/BASE VEHICLES MODULE

This module represents the transition from manned to unmanned operations. The storage/base vehicles module, SBVM, will house storage facilities for processed goods and the "hanger" for the manned and unmanned vehicles. Vehicles will be retrieved from the hanger using the MRMS.

4.4.5 RAW MATERIALS PROCESSING MODULE

This module, the RMPM, will house all the raw materials processing facilities.

This module is logically located between the processed materials storage facilities and the regolith mining support facilities.

4.4.6 MINING MODULE

This module will be the last SM deployed for the main body of the base. The mining module will hold all mining equipment and supporting transportation equipment (surface tracks, anchors). This module is deployed at the perimeter of the base so that mining operations may expand unimpeded by the base. The regolith mined will also be routed through this module to the RMPM.

4.4.7 PRIMARY POWER PLANT MODULE

This module is the very last module deployed because the PPPM, discussed in the ground rules section of this report, will be remotely piloted, via large rotational tracks, to a location providing adequate radiation shielding for the Phobos base -- the location could be inside the smaller crater within Stickney. The PPPM will also contain all cables or equipment necessary to transfer the power from the nuclear plant to the main body of the Phobos base. Mining and processing operations may begin as soon as the PPPM is operational.

4.4.8 MANNED SUPPORT

Initially, the Phobos base described by this report was targetted for manned deployment support of 6 men for 2 weeks. Upon review of the deployment sequence of events, all of the deployment events described could be accomplished by an artificial intelligence (AI) system or remotely controlled from a concurrent colonization effort on the surface of Mars. The manned capability for the Phobos base is still required to fulfill the needs of a wide range of space supply, transportation, exploratory and scientific missions.

4.5 OVERALL MASS ESTIMATES

A rough method for estimating a total base mass is presented in Appendix A of this report. Using graphite/epoxy compounds for the system module truss work yields a truss work mass of 14,500 kg for a truss bar radius of one inch and a truss size of six feet cubed. Most of the SM payload masses are unknown; however, a few estimates are available. The 5 megawatt nuclear planned designed by Texas A&M was estimated at 110,000 kg; two space station habitation modules (1985) were estimated at 40,000 kg. 100,000 kg was arbitrarily selected as an average SM payload mass. From these assumptions, the total base mass estimate becomes: 801,500 kg or about 1800 tons -- this will likely present structural integrity problems in the SM trusswork and will definitely limit the acceleration potential of the base on-orbit.

4.6 MACRO BASE CONFIGURATION STRENGTHS AND WEAKNESSES

The main strength of the macroscopic base configuration design relates to the underlying motivation of the NASA/University design programs: to present new, innovative ideas for the advancement of a permanent manned presence in space. The base design of Section 4.0 presents unique solutions to modularization of a large, complex industrial base which is constrained to a milli-g environment and only a few weeks deployment time for full-potential productivity. The macro base design defines problems, and some solutions, of problems previously undefined. With an overall concept to work with, design efforts may be continued in specific areas of special interest: application module interfacing, anchor systems, deployment systems, space vehicle supply and docking scenarios, power systems, structural integrity, life support systems, on-orbit and interplanetary propulsion systems, etc.

The overall weakness of the macroscopic base design stems from the broadness of the design effort. The aspects of the base design that are covered are done so on a conceptual level. Other aspects of the design are simply assumed as a ground rule: life support systems, power systems, on-orbit/interplanetary propulsion, crew evacuation. However, aspects of the base design addressed as a ground rule were those which already possess (in most cases) significant work directly and indirectly applicable to the current Phobos base design.

Other gaps in the design effort, cannot be peddled away as groundrules. Space vehicle rendezvous with the Phobos base for resupply -- both surface resupply and on-orbit resupply scenarios need to be defined. Base transportation cannot be assumed any longer -- the size of the project that has been defined necessitates a serious feasibility study to determine if the Phobos base can be transported into space in a cost effective manner. The structural integrity of the Phobos base for its on-orbit transportation role was essentially ignored, but the base size and mass estimates force the structural integrity issue.

5.0 MINING PROCEDURES

This section discusses mining equipment restrictions and requirements, versatility, and outlines an operational mining system. Mining strategies and required technologies will also be discussed.

5.1 EQUIPMENT RESTRICTIONS AND REQUIREMENTS

The physical conditions on the surface of Phobos pose restrictions on the mining equipment to be used. The main restrictions are the increased friction due to the near vacuum on the surface of Phobos[1] and the lack of any convective heat dissipation mechanism[2], both of which will affect the performance of the equipment. Another restriction is the possibility of cold welding of moving joints, also due to the high vacuum environment[3]. An additional restriction is posed by the very low gravity on the surface of Phobos which will require the mining equipment to be securely anchored or to be sufficiently massive to create enough reaction force to be able to mine the surface. The mining equipment should comply with certain requirements. The equipment must fit, efficiently packed, into the system modules. The mining system must be relocatible and expandable for surface versatility. The mining system should be able to avoid or reduce obstacles such as large rocks. The mining equipment should perform several tasks: surface mining, surface coring, surface tunnelling and safe haven burial. In order to achieve these tasks, the mining equipment should consist of several interchangeable mining components. The mining equipment should consist of simple components and each with a minimum of moving parts.

5.2 MINING CONCEPTS

This section presents the proposed mining concepts with a brief description of the components. The component descriptions are conceptual and serve to define system requirements.

5.2.1 SCOOPING CHAIN

The scooping chain mines regolith by scraping the surface of Phobos. Figure 5.1 shows the surface scraping component, which will then be attached to a system module.

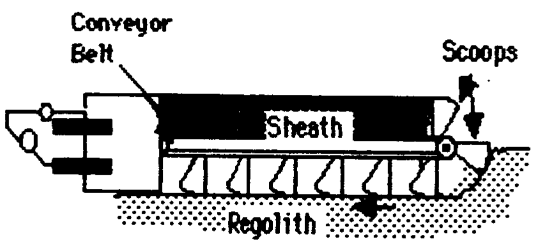


FIGURE 5.1 - Scooping Chain Concept

5.2.2 REGOLITH MELTING

Regolith melting is useful in tunnelling, coring, and safe haven burial. Several methods and components have been suggested for these tasks and reference 5.4 proposes several coring components. Consolidation melting creates a glass-lined hole with thick (≈1/2 of the hole radius) solid walls. This feature can be used to form walls composed of many solid hollow cylinders as shown in Figure 5.2. The regolith within the walls would then be removed with a scooping chain mechanism. This procedure could be used for safe haven pit excavation. Figure 5.3 shows a component which would form slabs of melted

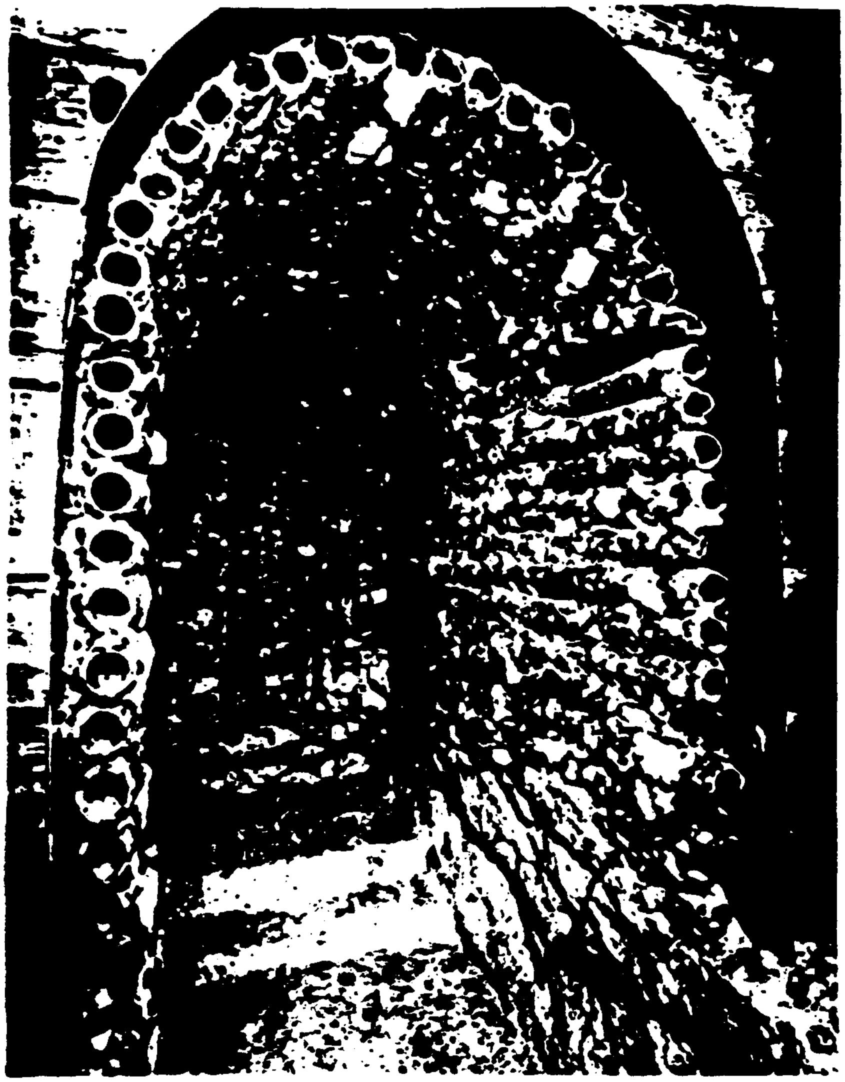


FIGURE 5.2 - Excavation Using Wall Melting

regolith that could be used for subsurface construction, shielding or storage.

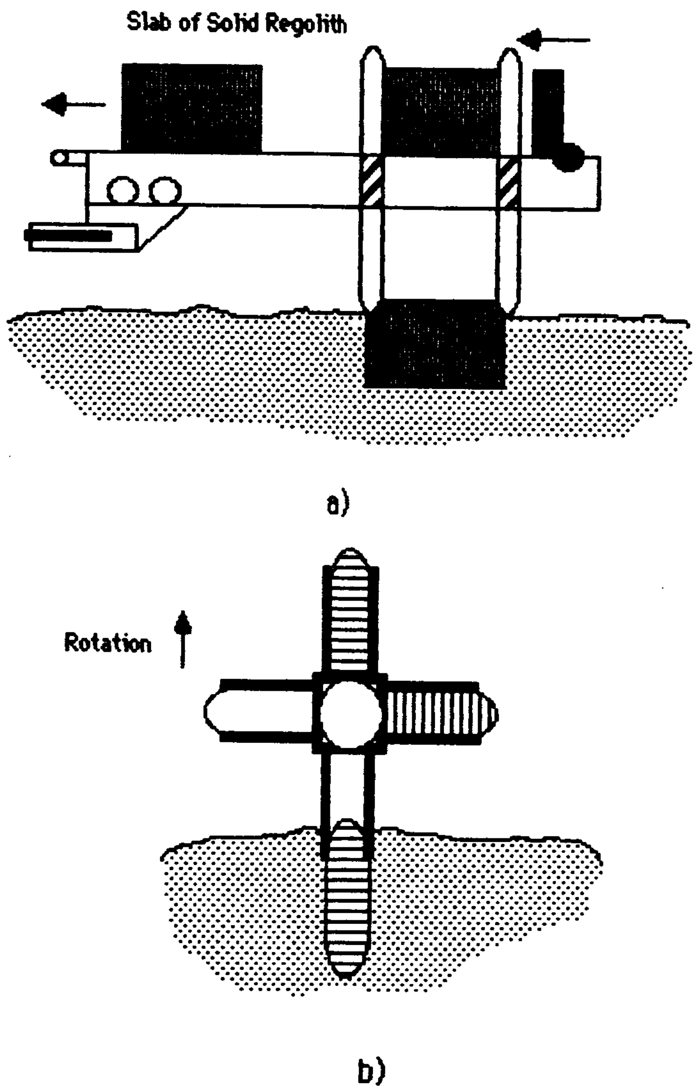


FIGURE 5.3 - Slab Melting Concept

The slab melter bites into the regolith and melts it with the high temperature surface inside the device. The slab melter is then pulled up and rotated until another slab melter is in place. The process is then repeated. Once the slab is rotated 180° a pusher then pushes this solid slab onto a conveyor belt feeding the processing unit. The slab melter assembly fits into a multidirectional joint.

This procedure is not favored for resource mining because heating the regolith at least to its melting point causes it to lose much of the desired volatile products, namely hydrogen and oxygen.

5.2.3 DRAGGED SCOOP

Figure 5.4 shows the dragged scoop concept. This method is inefficient since it is not easily automated. This is due to the need for the scoop to be redeployed. It also fails to provide effective obstacle avoidance.

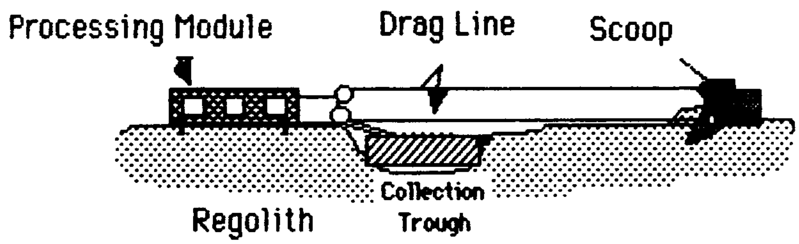


FIGURE 5.4 - Dragged Scoop

5.2.4 ROCK FRACTURING

In the advent of finding a solid rock obstacle, rock fracturing should be applied before the scooping chain starts its job. A method of fracturing rock by impact shock waves is illustrated in Figure 5.5. This is achieved by attaching a probe with an impact hammer. The hammer is driven by a piston with compressed CO_2 gas. Carbon dioxide is a by-product of the proposed regolith processing and should be readily available. Internal stesses in the rock are cumulative and repeated impacts will eventually crumble the rock, irrespective of the magnitude of the force of impact.

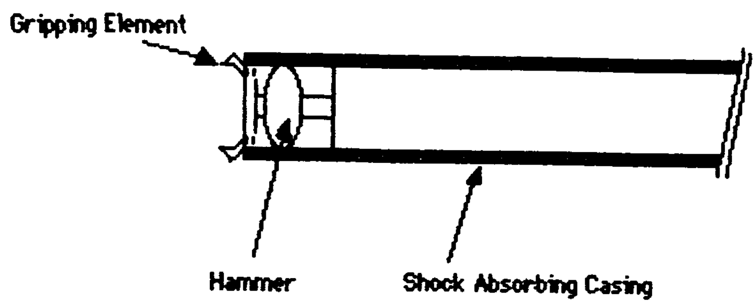


FIGURE 5.5 - Rock Fracturing Element

5.2.5 ORE CARTS

The required ore cart payloads can be initially sized using an assumed ore production capacity and a continuous operation. The time it takes for a cart to traverse the track circuit can be described by the expression:

$$T = L/V + t \qquad (5.1)$$

Where,

T = Round trip circuit track time
L = Round trip track length
V = Average speed along the circuit
t = Estimated off-loading time

The track length can be stated as the perimeter of a circular arc:

$$L = r(2 + \beta) \qquad (5.2)$$

Where,

r = Spoke radius
β = Angle between the spokes in radians

Desiring a load (mass) per trip, the product of the daily production requirement with the circuit time divided by the work-day length yields the requirement for a single mining station. For a given number of stations, the following equation results:

$$nS = T(D/W) \qquad (5.3)$$

Where,

- n = Number of mining stations
- S = Mass requirement for the ore cart
- D = Daily production requirement
- W = Length of work-day

Using a daily production rate (Earth day) of 250 metric tons of H_2O per day, assuming a 10% water recoverability factor, a spoke length of 1 km and an angle between the spokes of 30°, the round trip track length is:

$$L = r(2 + \beta) \qquad (5.2)$$

$$= 1\text{ km}(2 + 0.5236)$$

$$= 2.5236\text{ km}$$

Assuming an average track speed of 5 km/h and an off-loading time of 10 minutes:

$$T = L/V + t \qquad (5.1)$$

$$= (2.5236\text{ km} / 5\text{ km/h}) + 0.1667$$

$$= 0.671\text{ hours} \approx 41\text{ min.}$$

Now, using the two initial mining stations and a 22 hour work-day, the ore cart mass capacity is:

$$S = (T/n)(D/W) \qquad (5.3)$$

$$= (0.671\text{ h}/2)(250\text{ mt}/22\text{ h})$$

$$= 3.815\text{ mt per trip}$$

This is for a single ore cart per mining station. So each ore cart must be capable of 1.907 metric tons of regolith. The volume of this regolith will yield an initial estimate of the size the ore cart must accommodate.

$$V = S / d \qquad (5.4)$$

Where,
V = Ore cart volume
d = Density of regolith

Using a constant density for Phobos of 2000 kg/m^3 or 2 mt /m^3 , the cart volume is:

$$V = 1.907 \text{ mt} / 2 \text{ mt/m}^3$$
$$= 0.954 \text{ m}^3 \text{ per trip}$$

This volume corresponds to that of a cube with sides of 0.984 meter. The factor, D/nW, is also the expression of the required hourly rate of ore production for a single mining station. Using the same daily production requirement and work-day, the production rate is 5.682 metric tons per hour. The resulting volume is 2.841 m^3/h. These figures indicate that the assumed daily production requirement is adequately met by the proposed mining operation. Another implication of this low rate is that the slower mining motions necessary in a low-g environment can easily be accommodated with a minimum of impact on production.

5.3 MINING STRATEGIES

The mining can take place either on the surface or under the surface, as shown in Figure 5.6. Problems with surface mining include raised dust and an adequate anchoring system.

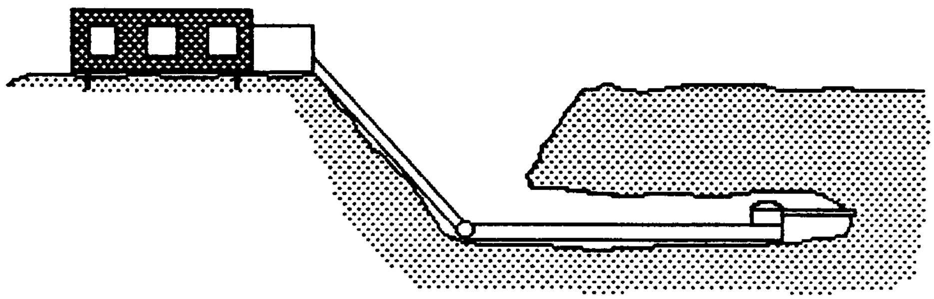


FIGURE 5.6 - Subsurface Mining

The mine station anchor should be sufficient for both horizontal and vertical reaction forces. Advantages of surface mining include:

a) ease in relocation an obstacle clearance;
b) ease of maneuvering on a the track for expansion and maintenance; and
c) regolith transportation to the processing station.

It was decided that a crawling, mining vehicle was unsuitable for use in the low gravity environment of Phobos.[4] A sealed system to minimize the amount of raised dust eliminates the first problem. Using a separate anchoring system can eliminate the second. The advantages to subsurface mining are: raised dust is not freed in as great quantities and normal reaction can be obtained from both the floor and the ceiling. This assumes the regolith can support tunnels. Disadvantages to subsurface mining include:

a) maintenance access;

b) cave-ins requiring support;

c) the need to transport regolith out of the hole; and

d) obstacle avoidance or clearing.

By applying the various mining components in view of the advantages and disadvantages a comparison of mining equipment and strategy can be made. Table 5.1 contains a decision matrix rating the various concepts for suitability to Phobos applications. From Table 5.1 the best choice for resource mining is the scooping chain. The disadvantages of surface mining are more easily overcome than those for subsurface mining. Above surface mining is the preferred method. However, both the scooping chain and a melting system are necessary for safe haven burial.

TABLE 5.1 - Decision Matrix

REQUIREMENT \ OPTION	SCOOPING CHAIN SYSTEM	DRAGGED SCOOP	MELTING
SIMPLICITY	1	3	2
ABOVE SURFACE OPS.	2	1	3
BELOW SURFACE OPS.	2	N/A	1
RESOURCE VOLUME	1	1	3
OBSTACLE CLEARANCE	1	3	2
EASE OF AUTOMATATION	1	2	1
SAFE HAVEN BURIAL	1	3	1

Simplicity is a measure of the mechanism's complication and ease of operation in normal circumstances. Normal circumstances are the same for each concept.

Above/Below Surface Operation is a rating of the suitability of the mechanism for above or below surface operations. Notice the dragged scoop cannot be used in subsurface operations.
Obstacle Clearance/Avoidance implies no special machinery has been installed to clear obstacles. The scooping chain was rated best for its ability to avoid obstacles.
Ease of Automation rates the ability for a complex artificial intelligence (AI) to direct the operation. Such AI factors as sensing and control were used to rate this category.
Safe Haven Burial rates a concept for its suitability to dig a hole for the safe haven.

5.4 OPERATIONAL PROCEDURES

Because of the requirement for continuous operation, the regolith transportation system on a closed loop of track. Power is supplied by this track and serves as a distribution bus for a series of scooping-chain mining stations. This relieves the necessity for batteries in the mining stations. Because the mining stations are restricted to the track, a method minimizing the track relocation was needed. The design presents a closed loop of track where mining takes place at the periphery.

5.4.1 TRACK LAYOUT

A possible configuration for the mining track layout is an arc with the center at the ore off-loading interface (Fig 5.7). This configuration provides a continuous one-way track for the ore carts. This is helpful in automation and to minimize the amount of track initially carried to Phobos. Mining stations will move clockwise about the arc. Digging patterns of the stations will themselves be arcs but not necessarily so. A second arc of track radially inward of the initial track should be deployed after the mining operation has been started. These two arcs will "leap-frog" inward to shorten the spoke length. As these spokes shorten, the excess track will be placed in the next spoke position. This will ensure continuous operation. Freed track from both the spoke and the two arcs can be used in the layout of the next spoke-arc combination (Fig. 5.8).

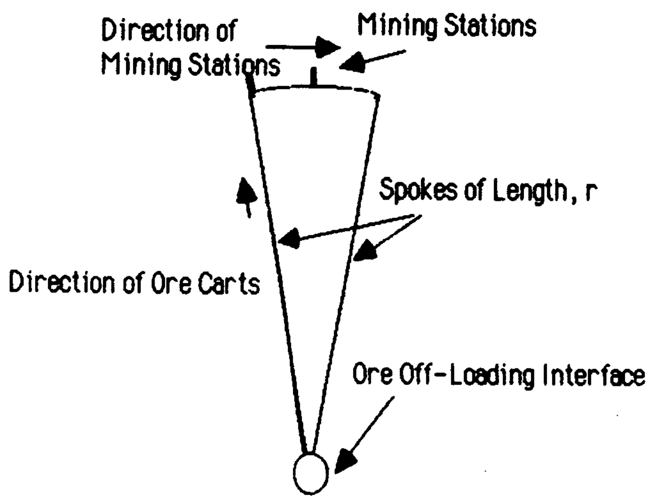


FIGURE 5.7 - Track Layout

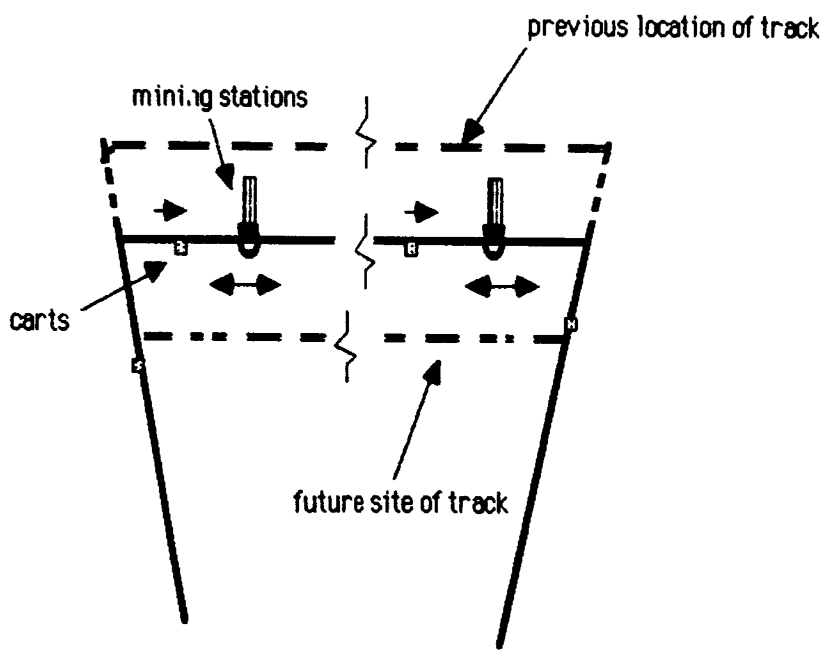


FIGURE 5.8a - Mining Station Relocation

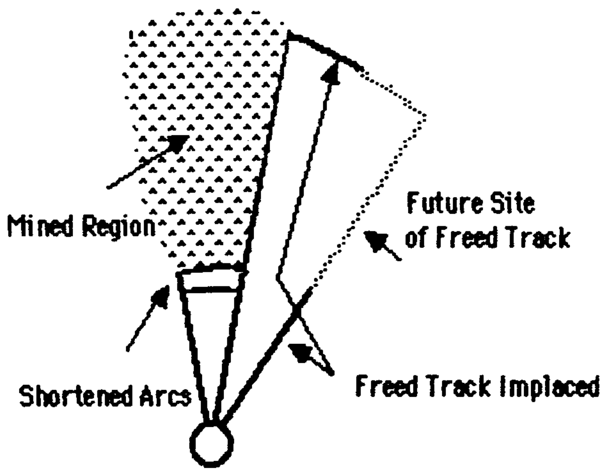


FIGURE 5.8b - Mining System Relocation

5.4.2 CART LOADING/UNLOADING

The carts are loaded by passing through the mining system module, shown in Figure 5.9, and dumping the scoops full of regolith into the cart. Since the system module is sitting on the tracks the cart will unhook temporarily from the main tracks on to local tracks located at the sides of the throughway.The system module has the driving and control systems for the mining operation and thus can control the cart for stopping and loading.

5.4.3 REQUIRED VEHICLES

For two mining stations and a round trip transit time of 0.683 hours, 2 ore carts per station should work efficiently by scaling ore excavation rates. Using a minimum of four ore carts and one rock fracturing unit, a minimum of two track driving bases are necessary. More driving bases will be needed for redundancy. A track relocating vehicle, maintenance and transportation vehicles are required. These vehicles as well as the track are discussed in Section 6.0.

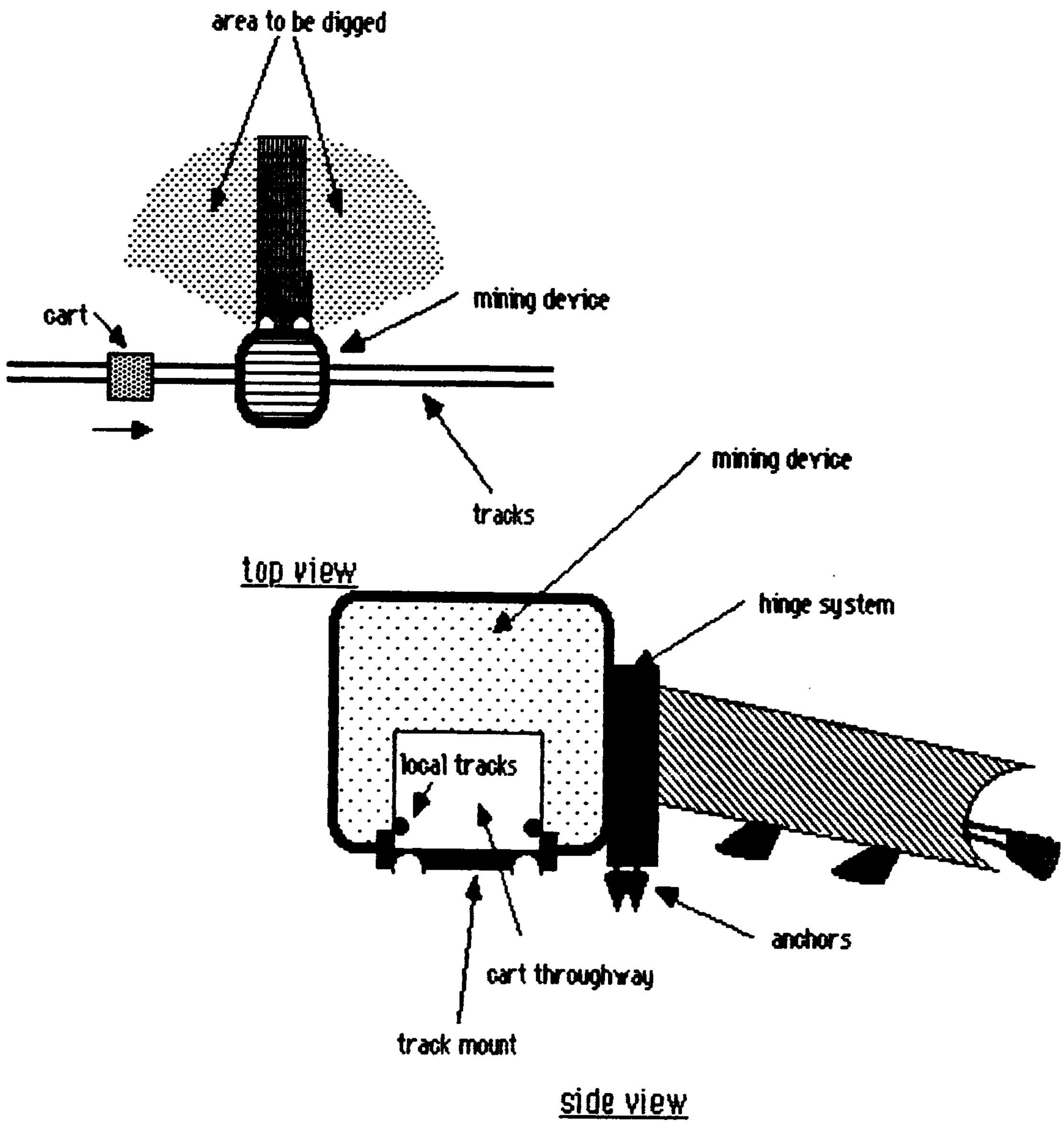


FIGURE 5.9 - Mining Station

5.5 REQUIRED TECHNOLOGIES

Some new technologies will be necessary for the above ideas to work mainly to overcome some of the restrictions posed by the environment of Phobos, as mentioned in section 5.1. Required technologies include:

a) new heat resistant alloys and coating methods to reduce wear and tear;

b) new lubricants that are efficient in vacuum are required for parts moving in a vacuum;

c) an anchoring system that will handle the horizontal and vertical reactions due to mining;

d) artificial intelligence sensing and control for automation of the mining operation; and

e) artificial intelligence maintenance techniques to repair mining malfunctions.

5.6 STRENGTHS AND WEAKNESSES

This section has set forward a mining system concept that fulfills the requirements posed by the environment of phobos and the nature of the mission. The environmental restrictions and general requirements as well as the basic operations of the mining system and required advances in technology have been defined. A short analysis showed that this mining system can easily meet the production goals of the base. The section lacks, however, any detailed analysis on the mining modules themselves and on the flow of the operations. Both the mining modules and the operational flow set up whole areas of research themselves.

6.0 SURFACE LOCOMOTION

This section will define possible required missions for Phobos' surface vehicles. Many modes of locomotion have been investigated for Phobos surface vehicles. Investigations have been based on lunar vehicle proposals and past research[1] which was considered for the Apollo missions. The design problems arising from the different environments of Phobos and the Moon will also be examined in this section. In order to fully develop a preliminary design for a surface vehicle, the Phobos surface terrain will be assumed to be similar to that of the Earth's moon. A decision matrix will be used to determine the surface vehicle or vehicles which could be used for Phobos base applications.

6.1 VEHICLE DESIGN DEFINITIONS

In order to have a fully autonomous base, some means of locomotion will be required. Locomotion could also be necessary for manned EVA's. The possible missions for a surface vehicle include:

- Standard maintenance
- Mining
- Transportation
- Surveying
- Exploration
- Large scale remote placement
- Initial base deployment
- All Purpose

6.2 DESIGN PROBLEMS FOR SURFACE LOCOMOTION ON PHOBOS

As mentioned above, research was based on surface vehicles which were considered for the Apollo missions; however Phobos presents many surface transportation problems which were not problems for the Earth's moon.

Phobos has one-thousands the gravity of Earth, thus gravitational effects from Mars make proximity operations analysis of the three body (Mars, Phobos, and vehicle) problem a realistic approximation for Phobos. Depending on the results of the Orbital Mechanics Group, proximity operations could drive the selection of the vehicle, but for preliminary design, gravitational effects of Mars will be negleted and the surface will be considered flat. The milli-g environment of Phobos yield reduced traction horsepower requirements and tipping stability problems; ie. the speed of the vehicle will have to be reduced when turning or cornering.

The vacuum environment will also influence the choice of locomotion. Cold welding will occur with poorly lubricated joints or rolling surfaces. Thus contacts must be protected or pressurized or an advance technology lubrication will have to be developed.

Surface characteristics is another consideration for vehicle design. Obstacle clearance and avoidance issues and the steepest slope or climbing gradient for the vehicle will have to be defined. The extent of grit or dust on the surface should be known together with the particle size. Problems for vehicles could include dust kick-up, rocket thrusters clogging, and sliding surface contamination.

For optimum locomotion system selection, the soil values, bearing pressure, smoothness of the surface, friction, and sinkage characteristics and cohesion must be known together with the distribution of these properties over the route that the vehicle will travel. For values that cannot be determined, Earth's moon will be used for the design and selection of the vehicle.

For manned vehicles, solar radiation protection will be included in the vehicle design. Meteor impact frequency will also be considered. The horizon distance is greatly reduced because of the size of Phobos; therefore some means of navigation will have to be considered.

6.3 VEHICLE DESIGN CONFIGURATIONS

Vehicle design will be based on four configurations:

- Rotational-tracks or Wheeled Vehicles
- Track-laying or Track-guided Vehicles
- Burrowing Vehicles
- Flying Vehicles

6.3.1 ROTATIONAL-TRACKS OR WHEELED VEHICLES

This type of vehicle will use wheels or rotational-tracks to propel itself. Some of the past proposals for the lunar vehicles include the Lunar Surface Exploration Vehicle and the Boeing MOLAB.

Wheeled vehicles will be considered for local area operations which will require maneuvering around obstacles. The wheels of the vehicle could have aluminum spokes with recessed steel webbing, the spokes deflecting radially and tangentially to simulate a pneumatic tire. With the steel webbing, a constant wheel width is maintained and the rolling resistance is kept constant. With increasing load, the contact area increases longitudinally producing no increase in bearing pressure. The chassis of the vehicle will be low and wide to produce a low center of mass. This type of vehicle could be used to perform necessary maintenance tasks around the base. The immediate problem of this type of vehicle is reduced traction horsepower.

The rotational-tracked vehicles (bull dozer, tank, half-tracks type) will be considered for long range operations and transport of large masses. The tracks will have extended ribs to allow more traction. To improve stability, the vehicle will have a low center of mass. The tracks should also be as far apart and as wide as possible. This type of vehicle is expected to have good mobility on the soft ground, good performance on rough surface, and good obstacle crossing. This vehicle will be used for the remote placement of the powerplant. Figure 6.1 depicts the wheeled and rotational-track vehicle configurations.

6.3.2 TRACK-LAYING OR TRACK-GUIDED VEHICLES

Track-laying vehicles will use track which is anchored to the Phobos surface or base to propel and steer the vehicles. The track may be laid by the vehicle as it progresses along a previously laid track or the track may be deployed in large folded, spring-released sections. All track systems will require an anchoring system to resist vehicle inertial forces. Track anchor systems will be small scale versions of the base anchor systems.

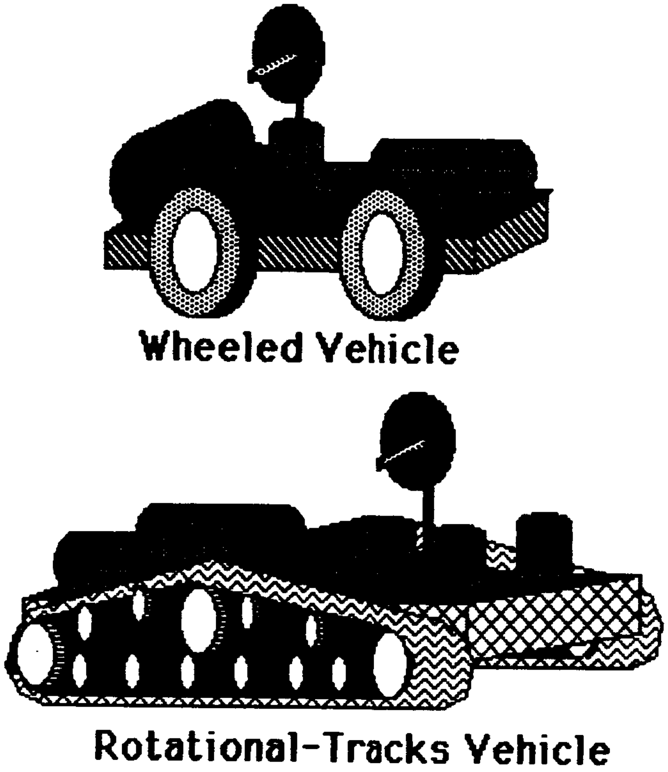


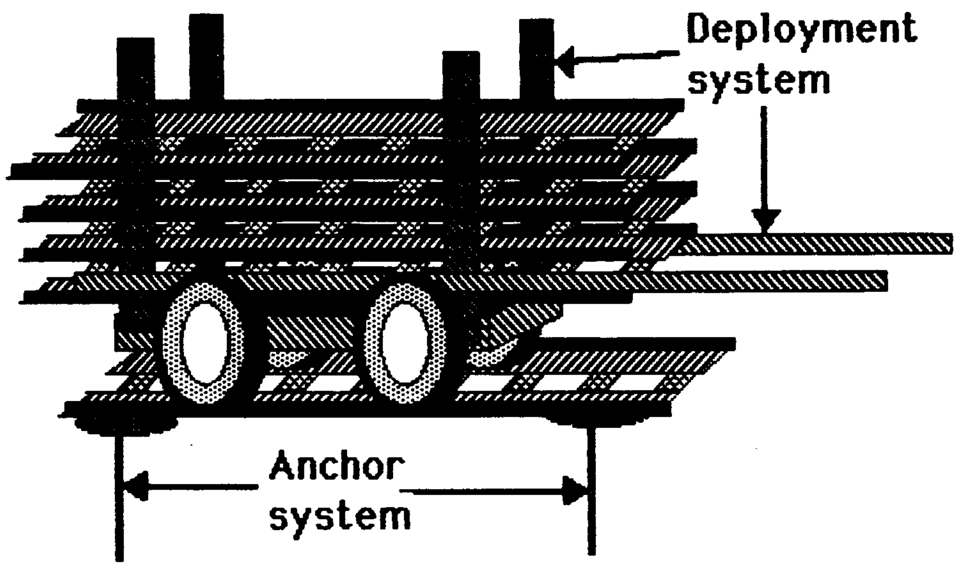
FIGURE 6.1 - Wheeled and Rotational-track Vehicles.

Track-guided vehicles will use a track which is suspended above the Phobos surface. The vehicle could be suspended below the track or ride above the track. The initial deployment of the track will require a complex deployment system, but the vehicle will not be restricted by surface obstacles. Figure 6.2 depicts the track configurations.

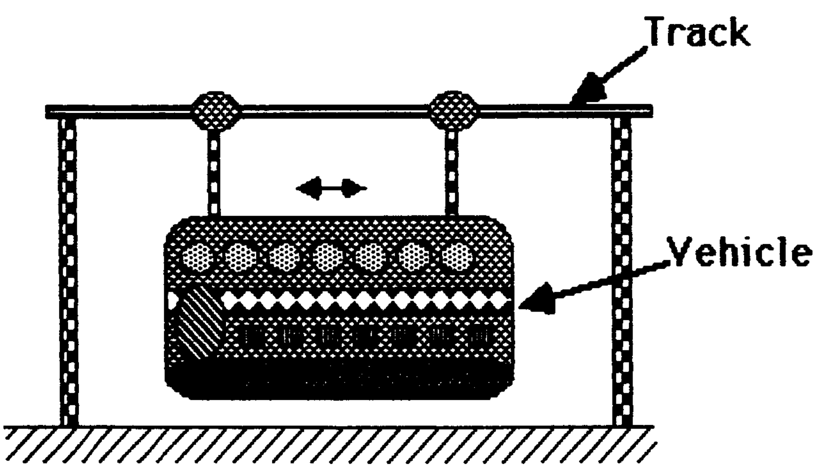
These type of vehicles could be used to transport equipment or regolith to areas which require transportation between two fixed points (mining operations). The vehicle could be capable of transporting large masses since the vehicle would be getting reaction and stabilization from the tracks.

A tracked vehicle will also be used to transport the Remote Manipulator System

(RMS). The RMS will travel along tracks which are mounted to the tops of each module. The RMS will use the base for reaction force by locking the vehicle to the tracks. The RMS will be an important part in the deployment of the base and mining operation.



Track-laying Vehicle



Track-guided Vehicle

FIGURE 6.2 - Track-laying and Track-guided Vehicles

6.3.3 BURROWING VEHICLES

This type of vehicle was proposed by the General Motors Defense Research Laboratories. The principle of this type of vehicle is based on using one or a pair of screws to plow and propel itself through loose surface material. The vehicle could tow other necessary vehicles through the tunnel it dug out. The vehicle could also operate above the surface by having the screws buried in the ground. Figure 6.3 depicts this configuration of a burrowing vehicle.

A burrowing vehicle would be very useful for tunneling. The concept will be the toughest vehicle to design since the soil parameters are not known. Conceivably, the vehicle could bury itself and remain stuck in the regolith; thus this vehicle is not a primary candidate for the Phobos base.

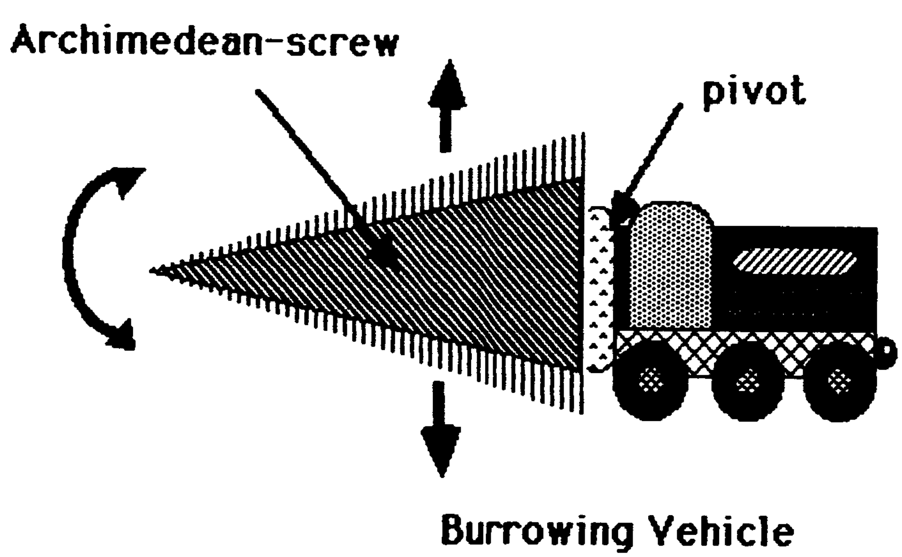


FIGURE 6.3 - Burrowing Vehicle

6.3.4 FLYING VEHICLES

This group of vehicles would use reaction jets for movement about the surface of Phobos. The advantages of a jet powered vehicle include increased surface mobility and the capability of going over large irregularities of the surface. The jet powered vehicles may be grouped into two categories: small scale vehicles like the Manned Maneuvering Unit (MMU) or Space Scooter Unit (SSU) and the larger scale frame-based vehicles. If the dust kick-up of the surface becomes a problem, the vehicle may have jumping shocks which will enable the vehicle to be kicked-off the ground for initial surface clearance, at which time the jets could be used. Figure 6.4 depicts the configuration of three flying vehicles. The control systems of these types of vehicles will have to be very sophisticated. With the milli-g environment, the vehicle could easily be lost in space or crash uncontrollable. An inertial navigation system is expected to have the capability to accomplish control and stability of the vehicles.

If enough reaction from the rockets were available, the framed based vehicle could be used for maintenance. This type of vehicle would be most advantageous for manned flight. The vehicle will be maneuverable and autonomous if necessary. The vehicle is the primary candidate for the transportation vehicle and the exploratory/surveying vehicle. A RMS will be installed on the vehicle for general tasks. A remote pilot control will be considered for an option.

The MMU and SSU will be useful to transport people to tasks which would require more flexibility than the frame based vehicle. The SSU will be advantageous because the person could leave the vehicle. The weakness of this idea is that the man will have to adapt to the milli-g environment. The MMU will restrict the persons movement within the back pack, but he could easily maneuver around the base for certain tasks.

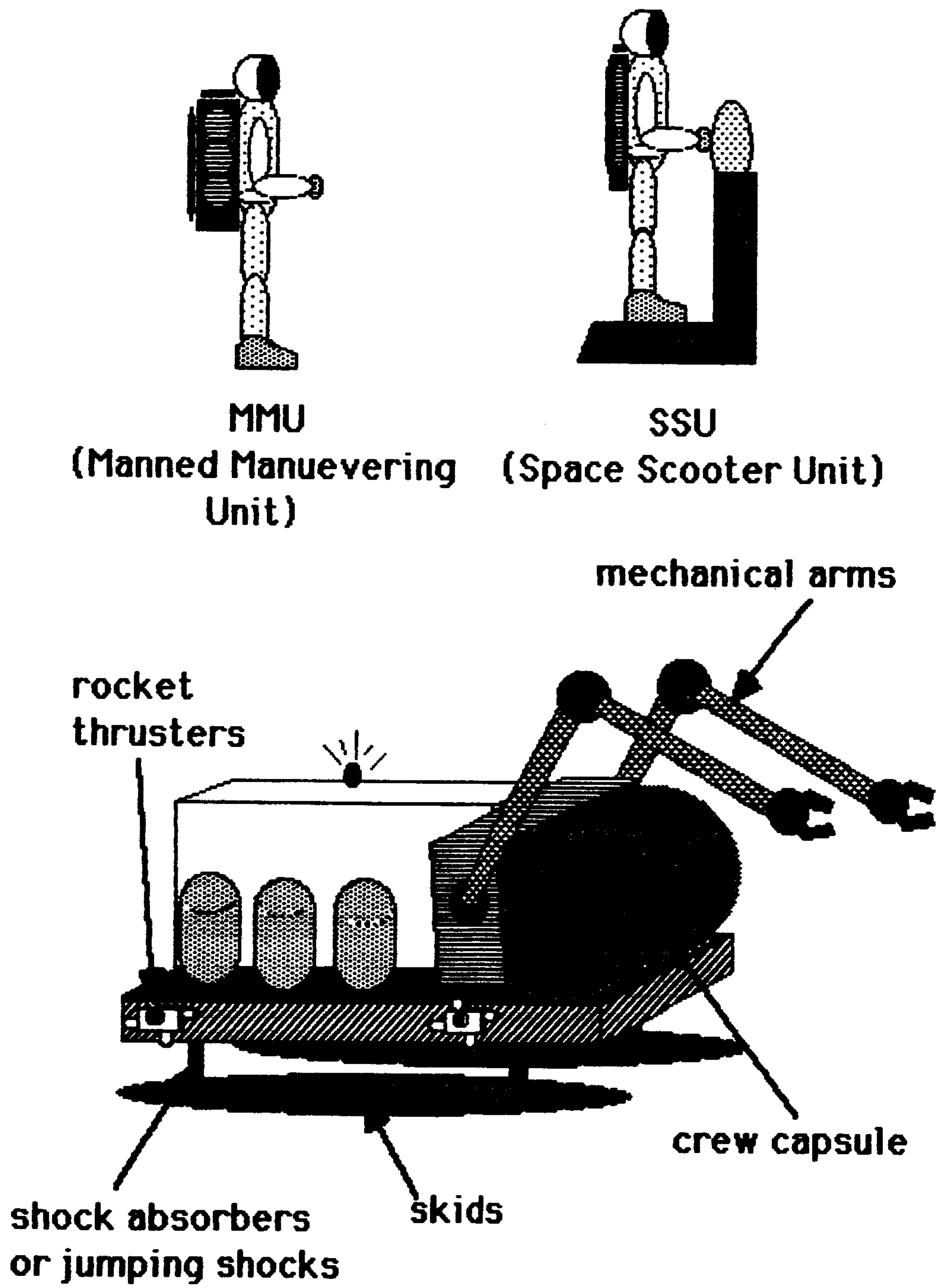


FIGURE 6.4 - Flying Vehicles

6.4 DECISION MATRIX FOR SURFACE LOCOMOTION

A decision matrix will be used to determine the best vehicle or vehicles for the Phobos base. The vehicle will be versatile enough to carry out many tasks. The vehicle may or may not be manned, depending on the requirements of the specific missions. The vehicle should have an autonomous or remote pilot control for the manned vehicles. The vehicles required for the operation of the base will be autonomous. The decision matrix which will be used to determine the mode of locomotion is shown in Table 6.1.

Terrain versatility - - the rotational tracked, tracked, and flying vehicles seem to be versatile on Phobos' surface. The flying vehicles obviously have the greatest advantage since they can fly over obstacles. All the vehicles will require some type of stabilizer because of the low gravity. The stabilization could be accomplished with tracks, reaction wheels, or rocket thrusters.

Environmental effects -- the surface vehicles will have an effect on the environment. With the surface contact, the vehicles will easily kick up dust which could reduce visibility or immobilize the vehicle.

Minimum moving parts -- the flying vehicles will have the least moving parts necessary for propulsion. The rotational tracked vehicle would potentially have the most moving parts. As mentioned before, moving parts would be a disadvantage since the vacuum could cause cold welding on moving surfaces.

TABLE 6.1 - Surface Vehicle Decision Matrix

REQUIREMENTS \ OPTIONS	ROTATIONAL TRACK	TRACK-LAYING	TRACK GUIDED	FLYING	MMU	SSU	RMS
TERRAIN VERSATILITY	3	3	2	1	1	1	3
MILLI-G STABILITY	4	3	3	1	1	1	2
ENVIRONMENT EFFECTS	4	2	2	2	2	2	1
MINIMUM MOVING PARTS	5	4	3	1	1	1	2
MANEUVERABILITY	3	5	5	1	1	1	5
HIGH SPEED	4	2	2	2	3	3	2
PAYLOAD WEIGHT	1	1	1	3	5	5	3
AUTONOMOUS	1	1	1	1	5	5	1

1 - 5 : Best - worst.

Maneuverability -- all vehicles possess some maneuverability, but the flying vehicles are the most maneuverable. The vehicles' speed will be limited by the escape velocity of Phobos unless some means of control is applied to keep the vehicles on the ground.

Payload weight -- the tracked vehicles seem to have the largest load capabilities. The worst load carriers are the personal vehicles such as the SSU and MMU. The RMS could be designed to support high loads since it will be anchored to the base. The tracked vehicles will also be capable to carry large loads.

Autonomous -- all vehicles could be designed for autonomous operation, but the unmanned vehicles which would be used for transporting mining equipment and used for maintenance would be the ones which would require the autonomous control. The autonomous control should include some means of remote control.

6.5 SURFACE VEHICLE DESIGN CONCLUSIONS

Four types of vehicles were determined to be required for the autonomous operation of the Phobos base:

- Remote Placement Vehicle (large structures),
- Remote Manipulator System,
- Magnetic Levitation Vehicle, and
- Flying Vehicle.

The Remote Placement Vehicle (RPV) (Section 6.5.1) will be used for the remote placement of the nuclear powerplant. The vehicle design was based on a proposal for a lunar (Earth) project.

The Remote Manipulator System (RMS) (Section 6.5.2) will have a primary role in the base deployment. It will also be used to keep the track system of the mining operation running. Details of this vehicle will be assumed closely related to the LEO Space Station RMS.

The Magnetic Levitation Vehicle (MLV) (Section 6.5.3) will be a generic vehicle which will use superconducting tracks to propell and levitate the regolith carts and mobile RMS. The track system will operate using electrical power from the powerplant. This type of vehicle is currently being studied as a mass driver.

The Flying Vehicle (FV) (Section 6.5.4) will be used for exploratory and surveying purposes. The vehicle will be capable of supporting a two man crew.

It has been determined that each vehicle could be a project in itself, thus this section will give a description of each vehicle and rough estimates on power consumption and mass.

6.5.1 REMOTE PLACEMENT VEHICLE

The RPV will be a rotational-tracked vehicle mounted to the Powerplant System Module. The tracks will be lowered from the module during the powerplant deployment. The vehicle will be used to move the powerplant a safe distance from the main base. A power cable will be used to transfer the electrical power to the base. As the powerplant is moved to the safe distance, a plow will be used to bury the power cable in the regolith for protection. Figure 6.5 illustrates the RPV with the power cable burial plow.

A power estimate was determined using some design proposals results from Reference 6.1. The data was taken from the Lunar International Laboratory - Translunar Exploration Vehicle (LIL-TLEV). The LIL-TLEV was six rotational-tracked vehicles in tandum arrangements similar to a train. Since the vehicles were slow moving vehicles (0.45 m/s) and each vehicle was moving at the same velocity, it was assumed that power has a linear relationship to the mass of the vehicle. The power relationship to the mass of the vehicle is depicted in Figure 6.6.

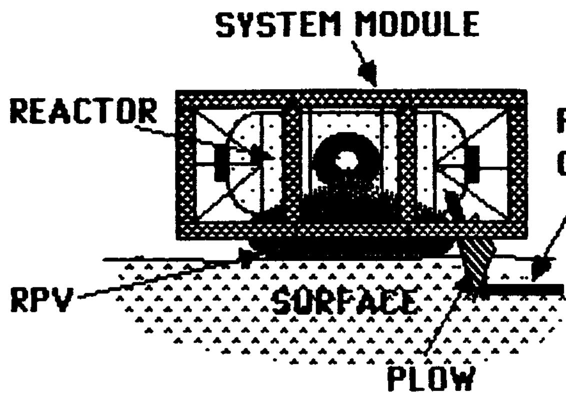


FIGURE 6.5 - RPV and Power Cable Burial Plow Scenario

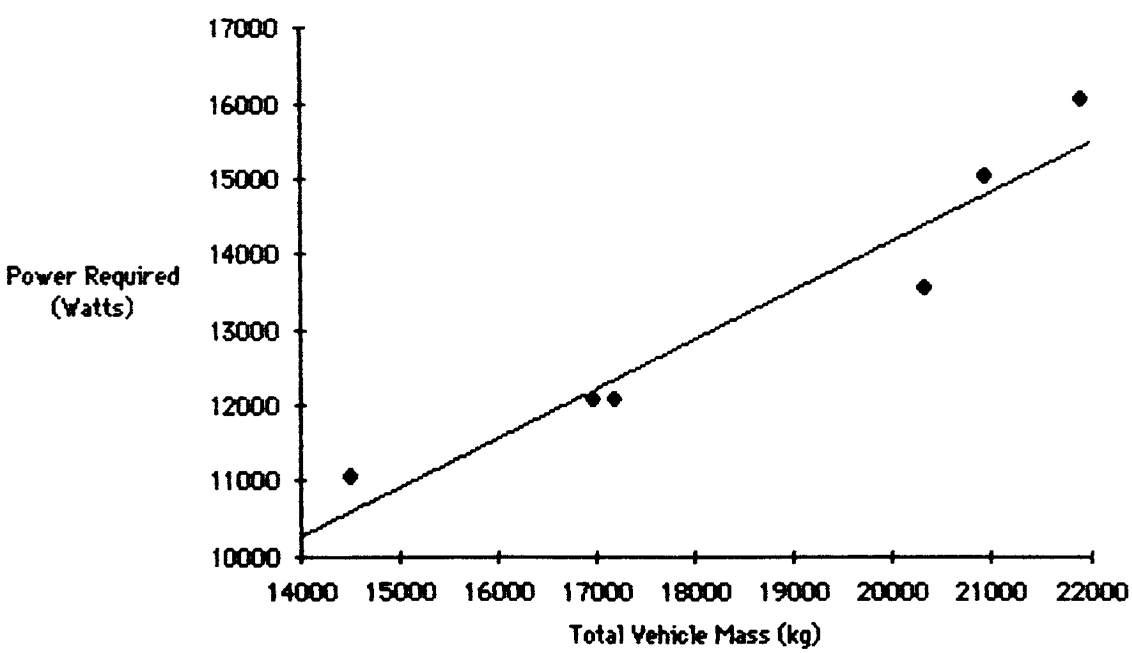


FIGURE 6.6 - Power vs. Mass for Rotational-Tracked Vehicles

The power estimate can be represented by Equation 6.1 using a best fit curve of data from the LIL-TLEV.

$$P_{RPV} = 1099.0 + 0.6546 * M_{RPV}, \qquad 6.1$$

where P_{RPV} is the power estimate (Watts) and

M_{RPV} is the total mass of the powerplant (kg).

The total mass of the powerplant can be calculated using Equation 6.2.

$$M_{RPV} = M_{reactor} + M_{module} + M_{rot.-track} \qquad 6.2$$

The mass of the rotational tracks is approximately 4228 kg[1]. The mass of the reactor is aproximately 100,000 kg[3]. The mass of the System Modules is approximatly 14,500 kg. Therefore, the power required for the RPV is approximately 80 kWatts.

6.5.2 REMOTE MANIPULATOR SYSTEM

The RMS will be a remote arm manipulator system which will be used for several tasks. The RMS will be similar to the LEO Space Station's RMS, thus details will be left for future studies.

The RMS will be used for the initial deployment of the base. The RMS will travel along tracks installed on each of the modules and it will perform some tasks such as relocating the deployment lever arms.

The RMS will also be used to relocate vehicles such as the FV and MLV; ie from surface to hangar. An RMS will also be installed on a MLV and it will be capable of moving and replacing the track system. The RMS will also be capable of performing some general maintenance requirements to the base and mining operation.

6.5.3 MAGNETIC LEVITATION VEHICLE

The MLV uses the basic concept of supporting and guiding the vehicle above a track by means of magnetic forces. Although numerous inventions have been devised to harness magnetic forces to provide stable vertical suspension, it has only been a few years with the advances in superconducting technologies that any real promise of success has been capable. Since this technology is still relatively new, little progress was found for a system which could be used for the Phobos base.

The main objective of the track and vehicle design is to provide guidance as well as levitation and propulsion. The design must include problems such as reduction of magnetic drag, route switching, ensuring freedom from accumulating debris, and heat transfer for the super conducting coils. Since the design is beyond the scope of this project, the design will be limited to a conceptual design in hopes of a future study to fill in details. Power and mass estimates were taken from Reference 3 using simple energy and mass formulas.

6.5.3.1 Design of the Tracks

The Phobos Track System will include a series of Linear Synchronous Motors (LSM) which will provide electrodynamic levitation and propulsion. The vehicle will have a powered or permanent stator magnet and reaction will come from the tracks. A Traffic Control Computer will monitor the activities of each MLV and with a series of switches will induce motion to the vehicles by orchestrating the LSM on the tracks.

All tracks will have a Connecting Track (CT) which will allow small angular alignments betweeen LSM tracks. The CT will be small in length compare to the LSM tracks such that the momentum of the vehicles will carry them across the CT. Each track will have a Small Scale Anchor System (SSAS) comparable to the base anchor system (Section 4.0). The SSAS will provide reaction for the MLV's and mining equipment.

Electrical power will come from the powerplant and base through a power cable. The power cable will have an inter-connecting devise to allow easy connections between tracks. Figure 6.7 depicts the conceptual design of a track.

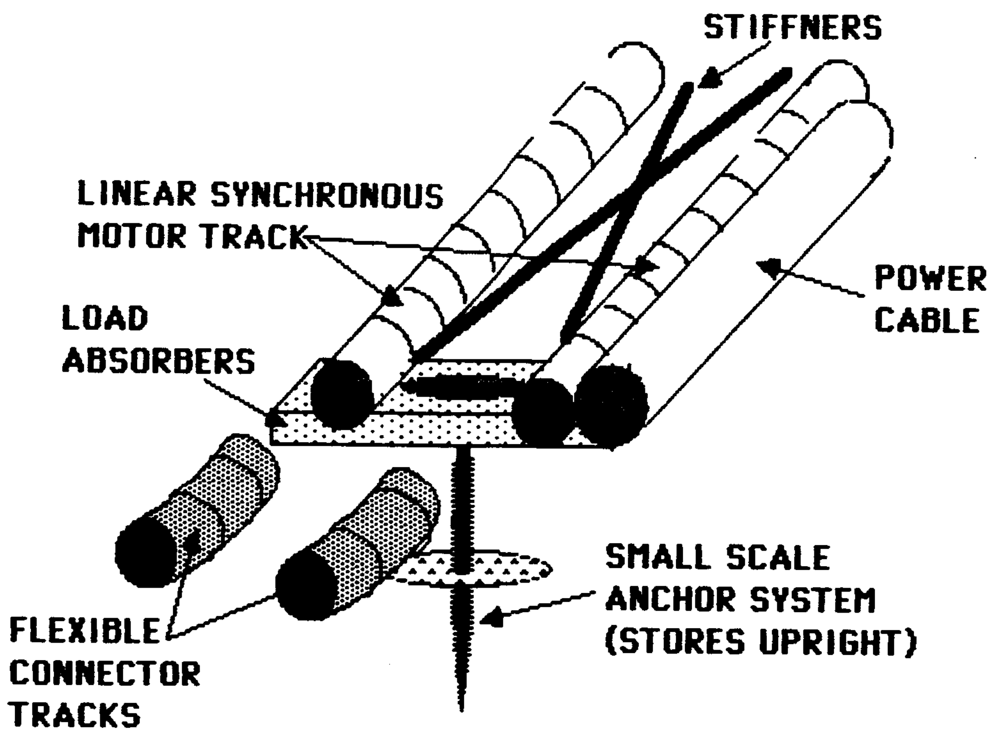


FIGURE 6.7 - Phobos Base Track Design

6.5.3.2 Design of the Magnetic Levitated Vehicle

The MLV will be a generic carrier for the mining operation. The regolith carts and RMS will be mounted to the MLV. The MLV will have the necessary equipment (ie. batteries, connectors) to provide the mining equipment with electrical power. A vehicle power cable will be connected to the main power cable when stationary to recharge the vehicle power source. For reaction from the LSM, the MLV will have permanent magnets or battery excited electro-magnets. The main power cable will recharge the magnets or batteries when the vehicle is stationary. The MLV will be able to accelerate or decelerate using the LSM.

The vehicle will have a suspension system which will absorb any discontinuities due to surface irregularities on the tracks. The suspension system will also have mechanical wheel restraints. The wheels will provide reaction for large perturbations or emergency mechanical braking. Figure 6.8 is a sketch of the MLV.

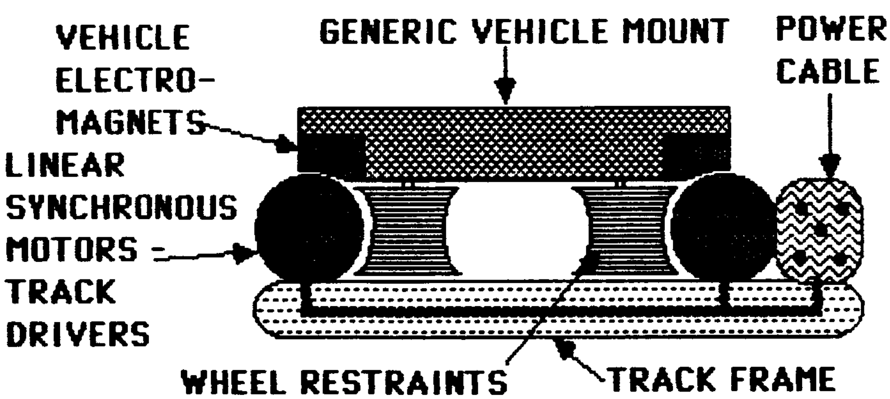


FIGURE 6.8 - Magnetic Levitated Vehicle

6.5.3.3 Power and Mass Estimates for the Track and Vehicle

Reference 2 was used to determine the mass of the track system. Using the data from the Erlangen test facility, the mass of the magnets were calculated as functions of thrust and lift. Because of the lack of data for a low speed, large mass driver, it was assumed that there was a linear relationship between the mass of the magnets and force the mass produces. Table 6.1 shows the results of the Erlangen test.

TABLE 6.1 - Erlangen test results

Total Mass / Rated Thrust	18 kg / 22 N
Total Mass / Rated Lift Force	540 kg / 60 kN

The main vehicle which will have to be shuttled back and forth on the tracks the most often is the regolith cart. The vehicle mass will be approximately 1875 kg (according to regolith load). Therefore, the lifting force requirement is 18.4 N. The vehicle will only be lifted approximately 5 mm^2 above the tracks. The available lifting force reduces exponentially as the distance is increased.

The track system will be set up so each regolith cart will travel approximately 2.5 km for one cycle (approximately 3600 s). The LSM will apply an impulse thrust to accelerate the MLV and the thrust requirement will be calculated using ΔV analysis. The impulse duration is approximately 70 seconds with a thrust of 18.75 N. This will accelerate (0.01 m/s^2) the vehicle to a speed of 0.7 m/s. The vehicle will concievably coast at a constant velocity the majority of the distance while the lifting force will be continuous and small compared to the thrust.

The energy (using kinetic and potential energy over the time durations) to complete the cycle required a power consumption of 13 Watts (with a conservative efficiency of 0.5). The power is relatively small compared to other power figures because of the low lift and velocity requirements. The majority of the efficiency loss will be to sensible heat. The total mass of the track system is approximately 13000 kg with 5 magnets for each track length (15 m).

6.5.4 FLYING VEHICLE

For a preliminary results for the FV, the proposed lunar flying vehicle[1] for the LIL-TLEV was considered. The vehicle was a two man exploratory vehicle capable of 4 hour duration with a range of 48 km and a maximum speed of 27 m/s This vehicle should be studied further because the environment on Phobos is 200 times smaller (gravity) than on the Moon. FV mass and power estimates were 12000 kg and 3.4 kWatts.

6.6 SURFACE LOCOMOTION STRENGTHS AND WEAKNESSES

The main strength of the surface locomotion design effort for the Phobos base is the NASA/University design program to present new innovative ideas for manned space programs. The design effort utilizes some current technology and advanced technologies which must be developed:

The FV and RMS vehicles are well developed concepts which currently have many available sources for a Phobos design vehicle.

The RPV is a relatively old design, but the Phobos environment will challenge any engineer for a successful milli-g vehicle. The greatest advantage of this vehicle is its versatility to large loads. The tracks can be easily modified to give enough traction horsepower for any type of payload.

The MLV is an old design concept, but it will require the new technology of superconductors to make the MLV an efficient vehicle. The greatest strength of this vehicle is that the milli-g environment will be an advantage rather than a disadvantage as for the RPV. The weakness of this type of vehicle design is that there is relatively few sources available on this subject. There is considerable concentration on mass drivers for high acceleration and low mass, but the MLV will require low acceleration and large mass. It is recommended that this type of propulsion be studied further by developing a math model of the track system.

7.0 RECOMMENDATIONS

The main strength of the design effort presented in this report is the wide range of problems which have been defined for a single mission -- to industrialize Phobos. Section 2.0 clearly stated the enormous wealth of raw materials available on Phobos and the currently known processes which can extract that wealth. Section 3.0 revealed the excellent logistics capability of Phobos compared to that of the Earth, Earth's Moon and Mars. Section 4.0 through 6.0 demonstrated a milli-g, high vacuum, high radiation environment may be tamed for industrial purposes using simplistic ideas based on current technology. Problems requiring technology development encountered during Phobos base analysis are well defined:

1) mechanical friction due to high vacuum;
2) lack of effective heat dissipation due to high vacuum;
3) lack of fully autonomous space operations due to the infancy of AI technology; and
4) affects of the excessive radiation exposure.

All these problems are currently being researched and the technology is expected to be available for use on a Phobos base. Several additional problems introduced in this report should be examined and defined completely. The following paragraphs suggest projects which are essential for determining the feasibility of an industrial base on Phobos.

From Section 2.0:

Precursory Mission to Phobos (Astronautical Engineering) -- A precursory probe mission to Phobos should be designed to confirm or deny the properties of

Phobos which are critical to the basis of the industrial base concept.

Market Survey (Material Science) -- The composition of Phobos has been defined (through an assumption), but the demand for the materials Phobos is capable of delivering have not been defined. A market survey should be conducted to evaluate the demand for Phobos materials beyond the year 2000. Possible supply sites should include Earth, Earth's Moon, LEOSS, Mars surface, asteroid belt and several outer planets.

Storage Cells (Civil Engineering) -- A means to store the materials produce by the Phobos processing plant should be determined. Storage for cryogenics, water, stable metals, and other producible goods should all been examined. Processing waste management should also be reviewed.

Material Processing Cycles (Chemical Engineering) -- a continuation of the work presented in Section 2.3.

From Section 3.0:

Phobos mass model (Aero/Astronautical Engineering) -- An accurate mass model that includes the asymmetrical mass distribution of Phobos could be derived generated.

A complete proximity operations study (Aero/Astronautical Engineering) -- A total acceleration gradient field could be generated using C-W equations modified to accommodate the gravity of Phobos.

Docking procedures (Aero/Astronautical Engineering) -- Complete rendezvous scenarios with delta Vs and trajectory analysis from possible starting points could be derived.

From Section 4.0:

Application Module Mounting System (Mechanical Engineering) -- Re-evaluate the current application module mounting system discussed in Section 4.3.2.

Anchor System (Civil Engineering) -- Re-evaluation of the current base anchor design and determination of the feasibility of such a design for use as an anchor for system modules, mining vehicle tracks and mining stations. The anchor design should fulfill all the requirements listed in Section 4.3.3 and insure the lateral stability of the anchored structures.

Deployment System (Mechanical Engineering) -- Re-evaluate the current deployment system design discussed in Section 4.3.4 and 4.4.

Base Structural Integrity (Aero/Astronautical Engineering) -- Design of a truss structure for the system module which will provide enough stiffness in the full tower configuration to withstand on-orbit accelerations. An acceleration limit for the base should be determined.

Manned Interfaces (Mechanical Engineering) -- Definition of the manned interfaces for a primarily manned and primarily unmanned Phobos base. All manned capability modules must have access to each other. Special pressurized maintenance areas for processing and mining maintenance should also be investigated.

From Section 5.0:

Coating Techniques and Lubricants for a High Vacuum Environment (Chemical Engineering) -- lubricants should offer efficient heat dissipation. Coatings should reduce friction between regolith and scoop .

Scooping Chain Mechanisms, Loading/Offloading Mechanisms, and Module/Track Interface (Mechanical Engineering) -- the scoop chain mechanism should have a minimum of moving parts, which could eventually clog with regolith. The size of the scoop should be set according to the production requirements previously defined and assuming the digging will take place very slowly. The loading and off-loading of the carts has to take place slowly to prevent the regolith from floating around. The system module for mining should contain all driving and control systems under the assumption that power will be delivered through the tracks.

Operations Strategies and Flow (Systems, Electrical Engineering) -- the motion of the carts, mining modules and other track vehicles should maximize the efficiency of the operation. Artificial intelligence will have to be developed in order to make the operations completely autonomous.

From Section 6.0:

Remote Placement Vehicle (Mechanical Engineering) -- Design of a large mass, slow moving, remotely piloted rotational tracked vehicle to be mounted to the system module of the primary powerplant.

Magnetic Levitated Vehicle (Electrical/Mechanical Engineering) -- Design of magnetic propulsion vehicles for large mass and slow moving payloads in a milli-g environment.

8.0 PROJECT MANAGEMENT

Table 8.1 shows the cost breakdowns for the project. Hours were reported weekly. The project was over-budget by almost $20,000.00. Material costs were not so severe. Man-hour projections from the proposal were too low. This is the reason for the overrun. The bulk of personnel time was spent on report preparation and dwarfed technical time by a factor of ten.

TABLE 8.1 - IGS Project Budget

Name:		Week 2	Week 3	Week 4	Week 5	Week 6
Mission Branch						
Linda Slifer		6	8.5	2.5	10.5	11
Jaime Chunda		6.5	2	5	6	5.5
Michele Stillman		4.5	4	9	13	9
Norman Fenlason		9	9	9	12	9
	Total:	26	23.5	25.5	41.5	34.5
Base Branch						
David Soto		3	3	3	8	5
Marcelo Gonzales		14	5	6	11	11
Robert Bailey		6.5	8	5	24	6
	Total:	23.5	16	14	43	22

Name:		Week 7	Week 8	Week 9	Week 10	Week 11
Mission Branch						
Linda Slifer		25	5.5	34.5	5	20
Jaime Chunda		15	2.5	11	13	9
Michele Stillman		21	3	20	20	8
Norman Fenlason		6	6	8	12	14
	Total:	67	17	73.5	50	51
Base Branch						
David Soto		9	3	28		
Marcelo Gonzales		15	4	19		
Robert Bailey		6	3	30		
	Total:	30	10	77	0	0

Name:	Week 12	Week 13
Mission Branch		
Linda Slifer	24	25
Jaime Chunda	4	12
Michele Stillman	5	9
Norman Fenlason	10	12

TABLE 8.1 - IGS Project Budget

	Total:	43	58

Base Branch

David Soto		9	14
Marcelo Gonzales		15	12
Robert Bailey		6	25
	Total:	30	51

Equipment and Supply Costs:

Rental of Small Computer Systems:
Mainframe Computer (Dual Cybers) Time Costs:
Computer Supplies:

Copying Costs:
Transparencies:

Budget

	Proposed	Actual	Ov
Personnel Costs	$27764.00	$48717.00	
Equipment Costs	$4719.00	$4988.02	
	==========	==========	
Total Cost	$32483.00	$53705.02	

TABLE 8.1 - IGS Project Budget

Total Hours	Hourly Rate	Personnel Costs
38.5	$22.00	$847.00
25	$15.00	$375.00
39.5	$15.00	$592.50
48	$25.00	$1200.00
		$3014.50
22	$22.00	$484.00
47	$15.00	$705.00
49.5	$22.00	$1089.00
		$2278.00
		==========
	Mission:	$5292.50
	Base:	$10585.00
		$15877.50

Total Hours	Hourly Rate	Personnel Costs
90	$22.00	$1980.00
50.5	$15.00	$757.50
72	$15.00	$1080.00
46	$25.00	$1150.00
		$4967.50
40	$22.0	$880.0
38	$15.0	$570.0
39	$22.0	$858.0
		$2308.0
	Mission:	$7275.5
	Base:	$14551.0
		$21826.5

Total Hours	Hourly Rate	Personnel Costs
49	$22.00	$1078.00
16	$15.00	$240.00
14	$15.00	$210.00
22	$25.00	$550.00

TABLE 8.1 - IGS Project Budget

		$2078.00
23	$22.00	$506.00
27	$15.00	$405.00
31	$22.00	$682.00
		$1593.00
	Mission:	$3671.00
	Base:	$7342.00
		$11013.00
	Total Personel Costs =	$48717.00
		$4290.00
		$24.69
		$13.33
	Total Computer Cost =	$4328.02
		$460.00
		$200.00
	Total Printing Cost =	$660.00
		==========
		$4988.0

er/Under Budget

$20953.00	
$269.02	
==========	
$21222.02	Over Budget

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APPENDIX A - SAMPLE CALCULATIONS

ESCAPE VELOCITY

An equivalent mass was computed from the computer-program-generated acceleration at the surface on the plus-X-axis.

Phobos equivalent mass backed out from computed acceleration at surface on +X-axis:

Three body solution:

$$\vec{F} = \frac{G M_1 M_2}{r^3} \vec{r}$$

$$F_x = \frac{G M_1 M_2}{r^3} r_x$$

$$r = r_x \text{ on x-axis}$$

$$F = M_2 a$$

$$M_2 a = \frac{G M_1 M_2}{r^3} r$$

$$a = \frac{G M_1}{r^2}$$

$$G M_1 = \mu$$

$$\mu = a r^2$$

Escape velocity:

$$V_{esc} = \sqrt{\frac{2 \mu}{r}}$$

$$= \sqrt{\frac{2 a r^2}{r}}$$

$$= \sqrt{2 a r}$$

$a = 0.00358661\ m/sec^2$

$r = 13500\ m$

$V_{esc-3\ body} = 9.8407\ m/sec$

Two-body solution:

$G = 6.672 \times 10^{-11}\ m^3/kg\ sec^2$

$M = 9.8 \times 10^{15}\ kg$

$V_{esc-2\ body} = 9.8421\ m/sec$

TOTAL MASS OF LIQUID HYDROGEN AND LIQUID OXYGEN FUEL THAT PHOBOS CAN PRODUCE

H_2 that can be produced = 675 250.00 kg

O_2 that can be produced = 5 412 950.00 kg

mass Oxygen(m_{O2})/mass Hydrogen(m_{H2}) = 7

H_2 is limiting factor:

$$m_{O2} = (7)(m_{H2})$$
$$= (7)(675\ 250.00)$$
$$= 4\ 726\ 750.00 \text{ kg}$$

MASS = $m_{O2} + m_{H2}$ = 5 402 750 kg   (Total mass of fuel per year)

MASS = 5402 mt

* from Ref. 3.4

PROJECTED MISSION FUEL USAGE PER YEAR

FROM PHOBOS:

1 TRIP(S) TO MOON	4.47×10^5 kg
6 TRIP(S) TO MARS SURFACE	5.52×10^5 kg
12 TRIP(S) TO LMOSS	10.44×10^5 kg
1 TRIP(S) TO SATURN	1.11×10^5 kg
	2154×10^6 kg = 2154 mt

SUPPLY DELTA V CALCULATIONS

The Space Shuttle carries about 30 000 ft/sec delta V, so this is an approximation of how much delta V it takes to over come the Earth's gravity well.* The delta V to overcome the gravity wells of other bodies was calculated using a delta V to mass ratio equal to that of the Earth. This may not be accurate due to atmospheric drag or lack of drag, but it should be of the correct order of magnitude.

30 000 ft/sec = 9.1442 km/sec

$R = (9.1442 \text{ km/sec})/(3.986 \times 10^{5}) \text{ kg}) = 2.2941 \times 10^{-5}$

$\Delta V_{body} = (\text{mass of body})(R)$

BODY	ΔV (km/sec)
Earth	9.1442
Mars	0.9876
Moon	0.1247

$\text{SUPPLY } \Delta V = \Delta V_{body} + \Delta V_{Table\ 3.2}$

* Dr. Fowler, Professor of Aerospace, University of Texas at Austin

STICKNEY CRATER DAYTIME SOLAR EXPOSURE ESTIMATE

The time that Stickney crater is exposed to solar radiation must be estimated to determine the annual radiation doses for the Phobos base crew and the amount of regolith necessary to supply the radiation protection. The small eccentricity (0.015) and inclination (1.02°) of the Phobos orbit about Mars were neglected for the daytime calculations; because of this simplification, the Phobos/Mars geometry can be considered as constant as it rotates about the sun. The sun is assumed to be at an infinite distance -- solar rays are parallel. Figure A.1 shows the three views of Phobos's orbit about Mars when the line of nodes of the Phobos orbit (referenced to the ecliptic) is perpendicular to the line of sight vector to the sun.

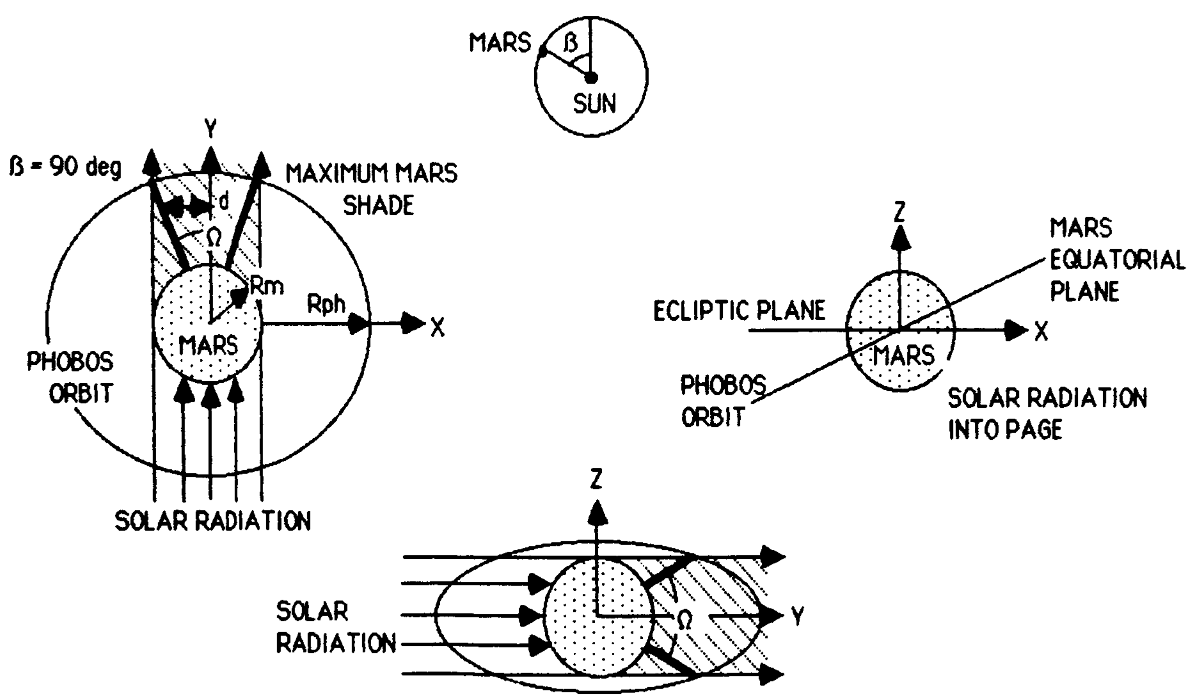

FIGURE A.1 - Sun / Mars / Phobos Geometry for Sunlight Calculations

As Mars revolves about the sun, the line of nodes of the Phobos orbit will rotate in the ecliptic plane and eventually lie directly on the sun line of sight vector (assuming Mars inclination to the ecliptic is zero). Figure A.2 shows the Phobos orientation, looking from the sun, when Mars has traversed approximately 70° relative the orientation in Figure A.1.

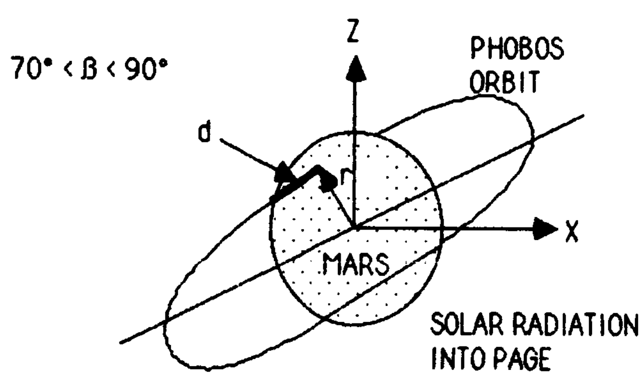

FIGURE A.2 - Shading Geometry Projected Perpendicular to Sun Line of Sight

The calculations for solar exposure for Phobos are outlined in the following algorithm.

DARK - TOTAL PHASE ANGLE OF THE PHOBOS ORBIT THROUGH WHICH STICKNEY IS IN DARKNESS
β - ANGLE BETWEEN SUN LINE OF SIGHT AND PHOBOS LINE OF NODES VECTORS
INITβ - β WHEN THE MARS SURFACE INITIALLY SHADES STICKNEY CRATER
COSβ - COSINE OF β
d - HALF THE LINEARIZED DISTANCE BETWEEN INTERSECTIONS OF THE PHOBOS ORBIT PROJECTION WITH THE MARS SURFACE FOR β > INITβ
Ω - PORTION OF DARK WHEN MARS SHADES STICKNEY
R_m - RADIUS OF MARS
n - MEAN MOTION OF MARS ABOUT THE SUN
R_{ph} - RADIUS OF PHOBOS ORBIT ABOUT MARS

calculate Ω and add Ω/day for $68.76° < \beta < 90.0°$

```
Ω = 0.0
for days=0 , while β < 90.0
    β = 68.76 + n * days
    r = R_ph * cos( β )
    d = R_m * cos( (r / R_m) * (Π / 2.0 ) )
    Ω = Ω + 2.0 * arctan( d / R_ph )
continue
```

calculate dark/year for Stickney shaded by Phobos and by Mars

$$DARK = \Omega * 4 + 180.0 * 365.0$$

calculate the percentage of sunlight per year for Stickney

$$LIGHT = (360.0 * 365.0 - DARK) / 360.0 * 365.0$$

From this procedure, the percentage of Stickney daytime per year is estimated to be 42.5%.

ANCHOR SYSTEM POWER AND DEPTH ANALYSIS

POWER REQUIREMENTS:

The power required to rotate the drill described in Section 4.3.3 was based on the simple relation:

$$P = wT$$

where: P = power

w = rate of rotation

T = applied torque to drill shaft

T was calculated based on the desired downforce of the anchor as it drilled through the regolith. Figure A-3 defines the variables used in the anchor system analysis.

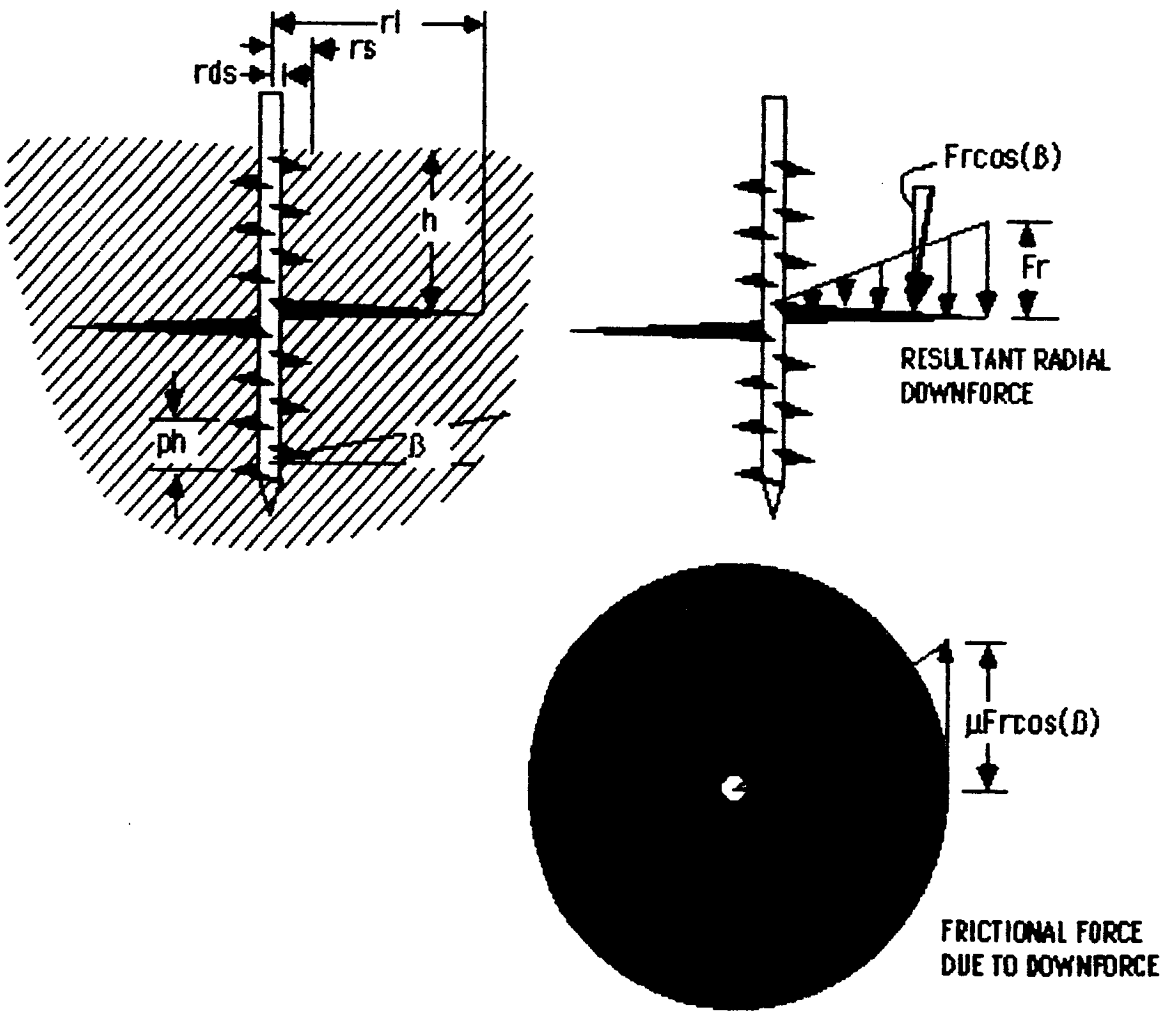

FIGURE A-3 - Anchor System Variable Definitions

Integrate the frictional force due to desired downforce around the surface of the anchor blades:

$$T = \underbrace{\int_0^{2\pi}\int_{r_{DS}}^{r_L} \underbrace{\underbrace{\frac{\mu\, Fr\, r}{r_L}\cos(\beta)}_{\text{FRICTION FORCE}}\; \underbrace{r}_{\text{MOMENT ARM}}}\, dr\, d\theta}_{\text{LARGE DIAMETER BLADE}} + \underbrace{n\int_0^{2\pi}\int_{r_{DS}}^{r_L} \frac{\mu\, Fr\, r}{r_L}\cos(\beta)\, r\, dr\, d\theta}_{\text{SMALL DIAMETER BLADE}}$$

$$= \int_0^{2\pi}\left[\frac{\mu\, Fr\cos(\beta)}{3r_L}\left(r_L^3 - r_{DS}^3 + n\,(r_s^3 - r_{DS}^3)\right)\right] d\theta$$

$$= 2\pi\left[\frac{\mu\, Fr\cos(\beta)}{3r_L}\left(r_L^3 - r_{DS}^3 + n\,(r_s^3 - r_{DS}^3)\right)\right] d\theta$$

The distributed normal force, Fr, is still unknown. Calculated desired downforce in terms of Fr:

$$F_D = \int_0^{2\pi}\int_{r_{DS}}^{r_L} \frac{Fr\, r}{r_L}\, dr\, d\theta + n\int_0^{2\pi}\int_{r_{DS}}^{r_L} \frac{Fr\, r}{r_L}\, dr\, d\theta$$

$$= \frac{2\pi Fr}{r_L}\left[\frac{(r_L^2 - r_{DS}^2)}{2} + n\,\frac{(r_s^2 - r_{DS}^2)}{2}\right]$$

$$= \frac{\pi Fr}{r_L}\left[r_L^2 + nr_s^2 - (n+1)r_{DS}^2\right]$$

rearranging:

$$Fr = \frac{r_L F_D}{\pi}\left(\frac{1}{r_L^2 + nr_s^2 - (n+1)r_{DS}^2}\right)$$

For small $\beta \Rightarrow \cos(\beta) = 1 \quad (\beta < 10°)$,

where $\beta = \tan^{-1}(p_h / 2\pi r_{DS})$.

where: P = power
T = applied torque to drill shaft
F_D = total downforce due to T
Fr = linear distributed downforce along blade radius
r_{DS} = radius of drill shaft
r_s = radius of small diameter blade
r_L = radius of large diameter blade
n = number of small blades
μ = coefficient of friction
β = blade pitch angle
p_h = vertical distance between blades

The following were constants in the anchor power calculations:

$r_{DS} = 2"$
$r_s = 6"$
$w = 30$ rpm
$n = 6$
$p_h = 2.2"$

At first the desired downforce was held constant at 100 lbf and the large diameter blade radius was varied. Table A-1 lists the results of the equations above.

TABLE A-1 - Torque and Power Requirements for Constant Downforce

BLADE DIAMETER (IN)	REQUIRED TORQUE (FT-LBF)	REQUIRED POWER (WATTS)
2	10303	38414345
4	2478	923763
6	1061	395763
8	588	219165
10	382	142383
12	277	103432
14	218	81355
16	181	67664
18	157	58498
20	139	51949
22	126	47008
24	116	43113
26	107	39933
28	100	37266
30	94	34980

Choose T as 100 ft-lbf; therefore, r_L = 28". Solve equations for P:

P = 37285 Watts.

DEPTH REQUIREMENTS:

Calculate weight of regolith directly above large diameter blade:

$$\begin{aligned} W &= mg \\ &= \rho V g \\ &= \rho(2\pi(r_L{}^2 - r_{DS}{}^2)h)g \end{aligned}$$

$$W = 2\pi\rho g h(r_L{}^2 - r_{DS}{}^2)$$

where: m = mass
g = acceleration of gravity
ρ = regolith density

V = volume of regolith above large diameter blade
h = depth of large blade beneath regolith surface

Calculate vertical shear on "walls" of cylindrical mass of regolith:

$$S = \sigma(A)$$
$$= \sigma(2\pi r_L h)$$

$$S = 2\pi r_L h\sigma$$

where: S = shear force
σ = cohesive strength of regolith
A = surface area of "cylinder"

Total anchor capacity is W + S:

$$F_a = W + S$$

$$F_a = 2\pi h(pg(r_L{}^2 - r_{DS}{}^2) + r_L\sigma)$$

The total anchor force, F_a, has a linear relationship with the anchor depth. Applying the following constants:

g = 0.004 m/s
σ = 0.1 N/cm^2
p = 2 g/cm^3
r_{DS} = 2"
r_L = 28"
h = 20 ft

yields:
W = 251 lbf
S = 1377 lbf
F_a = 1628 lbf.

BASE MASS ESTIMATES

Each face of a system module possesses 112 - 6 foot elements and 76 - 8.5 foot elements. Each system module has 8 faces => 896 - 6 foot elements and 608 - 8.5 foot elements or 10535 feet of truss elements per system module. Assuming each element has a radius of 1 inch, then the volume of all the truss elements in a SM is 230 ft^3. Assuming the truss material is a graphite/epoxy composite with a density of 0.07 lbm/in^3 the mass of the truss elements is 27,800 lbm or 12610 kg. Adding 15% for joint mass => Each system module has a mass of 14,500 kg. With an average of 100,000 kg payload per module (as presented in Section 4.4.8), the total average mass of a system module is 114,500 kg; and the mass of the entire base becomes 801,500 kg or 883.5 tons.

REGOLITH DEPTH ESTIMATE FOR RADIATION PROTECTION

From reference 4.5, the method to calculate the thickness of a material to supply total protection from radiation sources is detailed below.

Variables:

T - material thickness

D - material density, g/cm^3

E - particle energy level in MeV

Calculations:

$$A = 556.0 * \ln(1.0 + 5.48*10^{-6} * E^{1.8})$$

$$B = 1.0 - 1.667 * e^{-1.386 * \sqrt{D}}$$

$$T = A * B / D$$

From these calculations, using $D = 1.5\ g/cm^3$ for Phobos regolith, energy levels of $E = 10^3$ Mev and $E = 10^{20}$ total shielding regolith depths of approximately 2.3 meters and 171.6 meters respectively.

PATCHED CONIC DELTA V PROGRAM WITH FUEL USAGE COMPUTATIONS

This program called Condv was used to compute delta Vs and fuel requirements for interplanetary missions. It used a patched conic analysis to compute the delta V required for the mission, and it used an I_{sp} algorithm to compute the mass of fuel required for the mission.

For the patched conic transfer computations and the fuel mass computations all the input parameters are in metric. Kilometers are used instead of meters.

The output values following the program are listed in metric units unless otherwise specified.

```
      PROGRAM CONDV (INPUT,OUTPUT, TAPE 5=INPUT,TAPE 6=OUTPUT)
C
C     THIS PROGRAM WILL CALCULATE THE DELTA VS USING A CONIC SECTION
C     SUBROUTINE.
C
C     PARAMETER DEFINITIONS:
C       MU - GRAVITATIONAL PARAMETER (KM3/SEC2)
C       RS - RADIUS FROM THE SUN (KM)
C       VP - VELOCITY OF PLANET (KM/SEC)
C       RPERI - RADIUS OF ORBIT AROUND PLANTE (KM)
C       VCIRC - VELOCITY OF ORBIT AT RPERI (KM/SEC)
C
C     INPUT PARAMETERS
C       R1 - RADIUS OF PLANET 1 FROM SUN (KM)
C       R2 - RADIUS OF PLANET 2 FROM SUN (KM)
C       MU1 - GRAVITATIONAL PARAMETER OF PLANET 1 (KM3/SEC2)
C       MU2 - GRAVITATIONAL PARAMETER OF PLANET 2 (KM3/SEC2)
C       RPERI1 - INITIAL RADIUS AROUND PLANET 1 (KM)
C       RPERI2 - FINAL RADIUS AROUND PLANER 2 (KM)
C       MPAYLD - MASS OF PAYLOAD/STRUCTURE (KG)
C
C     ABBREVIATIONS
C       E - LEO SPACE STATION
C       M - MARS
C       J - JUPITER
C       S - SATURN
C       P - PHOBOS
C       L - LUNAR BASE
C       A - LMO SPACE STATION
C       U - URANUS
C       N - NEPTUNE
C       SUN - SUN
C
      REAL MU1,MU2,MUE,MUM,MUJ,MUS,MUP,MUL,MUA
      REAL MPAYLD,MFUEL,MTOT,ISP,MUU,MUN
C
C     CALCULATE DELTA V FROM PHOBOS TO LEOSS
        CALL PHOBOS (R1,MU1,RPERI1)
        CALL LEOSS (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        MPAYLD=200000
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE(6,10) DVTOT,MFUEL
 10     FORMAT ('1','PHOBOS TO LEOSS',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM PHOBOS TO LUNAR BASE
        CALL LUNAR (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE(6,20) DVTOT,MFUEL
 20     FORMAT ('PHOBOS TO MOON',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM PHOBOS TO JUPITER
        CALL JUPITER (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        MPAYLD=1000
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,30) DVTOT,MFUEL
 30     FORMAT ('PHOBOS TO JUPITER',T20,E12.6,' KM/SEC',
```

```
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM PHOBOS TO SATURN
        CALL SATURN (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,40) DVTOT,MFUEL
 40     FORMAT ('PHOBOS TO SATURN',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE THE DELTA V FROM PHOBOS TO URANUS
        CALL URANUS (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,170) DVTOT,MFUEL
 170    FORMAT ('PHOBOS TO URANUS',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE THE DELTA V FROM PHOBOS TO NEPTUNE
        CALL NEPTUNE (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,180) DVTOT,MFUEL
 180    FORMAT ('PHOBOS TO NEPTUNE',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO LEOSS
        CALL MARS (R1,MU1,RPERI1)
        CALL LEOSS (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        MPAYLD=200000
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,50) DVTOT,MFUEL
 50     FORMAT ('MARS TO LEOSS ',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO THE MOON
        CALL LUNAR (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,80) DVTOT,MFUEL
 80     FORMAT ('MARS TO THE MOON ',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO JUPITER
        CALL JUPITER (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        MPAYLD=1000
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,60) DVTOT,MFUEL
 60     FORMAT ('MARS TO JUPITER ',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO SATURN
        CALL SATURN (R2,MU2,RPERI2)
        CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
        CALL FUEL (DVTOT,MPAYLD,MFUEL)
        WRITE (6,70) DVTOT,MFUEL
 70     FORMAT ('MARS TO SATURN ',T20,E12.6,' KM/SEC',
     *   T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO URANUS
```

```
      CALL URANUS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,190) DVTOT,MFUEL
 190  FORMAT ('MARS TO URANUS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MARS TO NEPTUNE
      CALL NEPTUNE (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,200) DVTOT,MFUEL
 200  FORMAT ('MARS TO NEPTUNE',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM THE MOON TO LMOSS
      CALL LUNAR (R1,MU1,RPERI1)
      CALL LMOSS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=200000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,90) DVTOT,MFUEL
 90   FORMAT ('MOON TO LMOSS ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM THE MOON TO MARS
      CALL MARS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,100) DVTOT,MFUEL
 100  FORMAT ('MOON TO MARS ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MOON TO JUPITER
      CALL JUPITER (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=1000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,110) DVTOT,MFUEL
 110  FORMAT ('MOON TO JUPITER ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MOON TO SATURN
      CALL SATURN (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,120) DVTOT,MFUEL
 120  FORMAT ('MOON TO SATURN ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MOON TO URANUS
      CALL URANUS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,210) DVTOT,MFUEL
 210  FORMAT ('MOON TO URANUS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MOON TO NEPTUNE
      CALL NEPTUNE (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
```

```
      WRITE (6,220) DVTOT,MFUEL
 220  FORMAT ('MOON TO NEPTUNE',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM MOON TO PHOBOS
      CALL PHOBOS(R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=200000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,320) DVTOT,MFUEL
 320  FORMAT ('MOON TO PHOBOS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO JUPITER
      CALL LMOSS (R1,MU1,RPERI1)
      CALL JUPITER (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=1000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,130) DVTOT,MFUEL
 130  FORMAT ('LMOSS TO JUPITER ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO SATURN
      CALL SATURN (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,140) DVTOT,MFUEL
 140  FORMAT ('LMOSS TO SATURN ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO URANUS
      CALL URANUS(R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,230) DVTOT,MFUEL
 230  FORMAT ('LMOSS TO URANUS ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO NEPTUNE
      CALL NEPTUNE (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,240) DVTOT,MFUEL
 240  FORMAT ('LMOSS TO NEPTUNE ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO LEOSS
      CALL LEOSS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2, MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=200000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,250) DVTOT,MFUEL
 250  FORMAT ('LMOSS TO LEOSS ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LMOSS TO MOON
      CALL LUNAR (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,310) DVTOT,MFUEL
 310  FORMAT ('LMOSS TO MOON',T20,E12.6,' KM/SEC',
```

```
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO JUPITER
      CALL LEOSS (R1,MU1,RPERI1)
      CALL JUPITER (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=1000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,150) DVTOT,MFUEL
 150  FORMAT ('LEOSS TO JUPITER ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO SATURN
      CALL SATURN (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,160) DVTOT,MFUEL
 160  FORMAT ('LEOSS TO SATURN ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO URANUS
      CALL URANUS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,260) DVTOT,MFUEL
 260  FORMAT ('LEOSS TO URANUS ',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO NEPTUNE
      CALL NEPTUNE (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,270) DVTOT,MFUEL
 270  FORMAT ('LEOSS TO NEPTUNE',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO LMOSS
      CALL LMOSS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      MPAYLD=200000
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,280) DVTOT,MFUEL
 280  FORMAT ('LEOSS TO LMOSS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO PHOBOS
      CALL PHOBOS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,290) DVTOT,MFUEL
 290  FORMAT ('LEOSS TO PHOBOS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     CALCULATE DELTA V FROM LEOSS TO MARS
      CALL MARS (R2,MU2,RPERI2)
      CALL CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
      CALL FUEL (DVTOT,MPAYLD,MFUEL)
      WRITE (6,300) DVTOT,MFUEL
 300  FORMAT ('LEOSS TO MARS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
      STOP
```

```
      END
C
      SUBROUTINE PHOBOS (RSM,MUM,RPERIP)
        REAL MUM
        RSM=227.8E6
        MUM=4.305E4
        RPERIP=9378
      RETURN
      END
C
      SUBROUTINE MARS (RSM,MUM,RPERIM)
        REAL MUM
        RSM=227.8E6
        MUM=4.305E4
        RPERIM=3380
      RETURN
      END
C
      SUBROUTINE LUNAR (RSE,MUE,RPERIL)
        REAL MUE
        RSE=149.5E6
        MUE=3.986E5
        RPERIL=384400
      RETURN
      END
C
      SUBROUTINE LMOSS (RSM,MUM,RPERIA)
        REAL MUM
        RSM=227.8E6
        MUM=4.305E4
        RPERIA=3537.03
      RETURN
      END
C
      SUBROUTINE LEOSS (RSE,MUE,RPERIE)
        REAL MUE
        RSE=149.5E6
        MUE=3.986E5
        RPERIE=6841
      RETURN
      END
C
      SUBROUTINE JUPITER (RSJ,MUJ,RPERIJ)
        REAL MUJ
        RSJ=778E6
        MUJ=1.268E8
        RPERIJ=71666.32
      RETURN
      END
C
      SUBROUTINE SATURN (RSS,MUS,RPERIS)
        REAL MUS
        RSS=1426E6
        MUS=3.795E7
        RPERIS=60696.32
      RETURN
      END
C
      SUBROUTINE URANUS (RSU,MUU,RPERIU)
        REAL MUU
        RSU=2868E6
        MUU=5.820E6
```

```
      RPERIU=23826.32
    RETURN
    END
C
    SUBROUTINE NEPTUNE (RSN,MUN,RPERIN)
      REAL MUN
      RSN=4494E6
      MUN=6.896E6
      RPERIN=22616.32
    RETURN
    END
C
    SUBROUTINE CONIC (R1,R2,MU1,MU2,RPERI1,RPERI2,DVTOT)
C
C   THIS SUBROUTINE WILL CALCULATE A PATCHED CONIC DELTAV WHEN
C   GIVEN THE FOLLOWING DATA:
C     R1 - RADIUS OF PLANET 1 (KM)
C     R2 - RADIUS OF PLANET 2 (KM)
C     MU1 - GRAVITATIONAL PARAMETER OF PLANET 1 (KM3/SEC2)
C     MU2 - GRAVITATIONAL PARAMETER OF PLANET 2 (KM3/SEC2)
C     RPERI1 - INITIAL RADIUS ABOUT PLANET 1 (KM)
C     RPERI2 - FINAL RADIUS ABOUT PLANET 2 (KM)
C
C   OUTPUT PARAMETERS
C     DVTOT - TOTAL DELTA V TO DO TRANSFER
C
C   OTHER PARAMETER DEFINITIONS
C     VP - VELOCITY OF PLANET
C     VCIRC - CIRCULAR VELOCITY AROUND THE PLANET
C     VT - TRANSFER VELOCITY
C
    REAL MUSUN,MU1,MU2
C
    MUSUN=1.327E11
C
C   TRANSFER ENERGY
      ENERGY=-MUSUN/(R1+R2)
C   FIRST TRANSFER VELOCITY
      VT1=SQRT(2*(MUSUN/R1+ENERGY))
C   VELOCITY OF PLANET 1
      VP1=SQRT(MUSUN/R1)
C   V INFINITY AT PLANET 1
      VINF1=VT1-VP1
C   V AT PERIAPSIS AT PLANET 1
      VPERI1=SQRT(VINF1**2+2*MU1/RPERI1)
C   CIRCULAR VELOCITY AT PLANET 1
      VCIRC1=SQRT(MU1/RPERI1)
C   DELTA V 1
      DV1=ABS(VPERI1-VCIRC1)
C   SECOND TRANSFER VELOCITY
      VT2=SQRT(2*(MUSUN/R2+ENERGY))
C   VELOCITY OF PLANET 2
      VP2=SQRT(MUSUN/R2)
C   V INFINTIY AT PLANET 2
      VINF2=VT2-VP2
C   V AT PERIAPSIS AT PLANET 2
      VPERI2=SQRT(VINF2**2+2*MU2/RPERI2)
C   CIRCULAR VELOCITY AT PLANET 2
      VCIRC2=SQRT(MU2/RPERI2)
C   DELTA V 2
      DV2=ABS(VPERI2-VCIRC2)
C   TOTAL DELTA V
```

```
      DVTOT=DV1+DV2
      RETURN
      END
C
      SUBROUTINE FUEL (DVTOT,MPAYLD,MFUEL)
C
      REAL MPAYLD,MFUEL,MTOT,ISP
C
C     PARAMETER DEFINTIONS
C       DVTOT - TOTAL DELTA V (KM/SEC)
C       MPAYLD - MASS OF PAYLOAD/STRUCTURE (KG)
C       MFUEL - MASS OF FUEL (KG)
C       ISP - SPECIFIC IMPULSE (SEC)
C       G - GRAVIATIONAL ACCELERATION OF EARTH (KM/SEC2)
C       MTOT - INITIAL/TOTAL MASS OF VEHICLE (KG)
C
C     INPUT PARAMETERS
      ISP=360
      G=.00980665
C
C     CALCULATIONS
      MTOT=MPAYLD*EXP(DVTOT/(ISP*G))
      MFUEL=MTOT-MPAYLD
C
      RETURN
      END
```

PHOBOS TO LEOSS	.543923E+01 KM/SEC	.733559E+06 KG
PHOBOS TO MOON	.414339E+01 KM/SEC	.446744E+06 KG
PHOBOS TO JUPITER	.220521E+02 KM/SEC	.515136E+06 KG
PHOBOS TO SATURN	.166547E+02 KM/SEC	.110891E+06 KG
PHOBOS TO URANUS	.139544E+02 KM/SEC	.510735E+05 KG
PHOBOS TO NEPTUNE	.150246E+02 KM/SEC	.695116E+05 KG
MARS TO LEOSS	.568811E+01 KM/SEC	.801746E+06 KG
MARS TO THE MOON	.439227E+01 KM/SEC	.493982E+06 KG
MARS TO JUPITER	.217596E+02 KM/SEC	.474086E+06 KG
MARS TO SATURN	.161738E+02 KM/SEC	.966412E+05 KG
MARS TO URANUS	.133722E+02 KM/SEC	.431563E+05 KG
MARS TO NEPTUNE	.144083E+02 KM/SEC	.582173E+05 KG
MOON TO LMOSS	.437231E+01 KM/SEC	.490071E+06 KG
MOON TO MARS	.439227E+01 KM/SEC	.493982E+06 KG
MOON TO JUPITER	.255851E+02 KM/SEC	.140300E+07 KG
MOON TO SATURN	.201478E+02 KM/SEC	.299951E+06 KG
MOON TO URANUS	.173168E+02 KM/SEC	.133970E+06 KG
MOON TO NEPTUNE	.182908E+02 KM/SEC	.176852E+06 KG
MOON TO PHOBOS	.414339E+01 KM/SEC	.446744E+06 KG
LMOSS TO JUPITER	.217664E+02 KM/SEC	.475006E+06 KG
LMOSS TO SATURN	.161915E+02 KM/SEC	.971318E+05 KG
LMOSS TO URANUS	.133960E+02 KM/SEC	.434554E+05 KG
LMOSS TO NEPTUNE	.144342E+02 KM/SEC	.586539E+05 KG
LMOSS TO LEOSS	.566816E+01 KM/SEC	.796100E+06 KG
LMOSS TO MOON	.437231E+01 KM/SEC	.490071E+06 KG
LEOSS TO JUPITER	.239819E+02 KM/SEC	.890576E+06 KG
LEOSS TO SATURN	.180556E+02 KM/SEC	.165391E+06 KG
LEOSS TO URANUS	.149425E+02 KM/SEC	.678905E+05 KG
LEOSS TO NEPTUNE	.158180E+02 KM/SEC	.872797E+05 KG
LEOSS TO LMOSS	.566816E+01 KM/SEC	.796100E+06 KG
LEOSS TO PHOBOS	.543923E+01 KM/SEC	.733559E+06 KG
LEOSS TO MARS	.568811E+01 KM/SEC	.801746E+06 KG

HOHMANN TRANSFER DELTA V PROGRAM WITH FUEL USAGE COMPUTATIONS

This program called Hohdv was used to compute delta Vs and fuel requirement for missions about one planet. Hohdv uses a generic Hohmann transfer analysis to compute the delta V required for the mission, and it used an I_{sp} algorithm to compute the mass of fuel required for the mission.

For the Hohmann transfer computations and the fuel mass computations all the input parameters are in metric units. Kilometers are used instead of meters.

The output values following the program are also metric units.

```
      PROGRAM HOHDV (INPUT,OUTPUT,TAPE 5=INPUT, TAPE 6=OUTPUT)
C
C     THIS PROGRAM WILL COMPUT HOHMANN TRANSFER DELTA VS
C
      REAL MUMARS,MUERTH,MU
      REAL MPAYLD,MFUEL,MTOT,ISP
C
C     INPUT VARIABLES
        RPHOB=9378
        RLMOSS=3537.03
        RMARS=3380
        RMOON=384400
        RLEOSS=6841
        MUMARS=4.305E4
        MUERTH=3.986E5
        MPAYLD=200000
C
C     FIND DELTA V FROM PHOBOS TO LMOSS
        R1=RPHOB
        R2=RLMOSS
        MU=MUMARS
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,10) DV,MFUEL
 10     FORMAT ('1','PHOBOS TO LMOSS',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     FIND DELTA V FROM PHOBOS TO MARS
        R1=RPHOB
        R2=RMARS
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,20) DV,MFUEL
 20     FORMAT ('PHOBOS TO MARS',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     FIND DELTA V FROM MARS TO LMOSS
        R1=RMARS
        R2=RLMOSS
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,30) DV,MFUEL
 30     FORMAT ('MARS TO LMOSS',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     FIND DELTA V FROM LMOSS TO PHOBOS
        R1=RLMOSS
        R2=RPHOB
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,40) DV,MFUEL
 40     FORMAT ('LMOSS TO PHOBOS',T20,E12.6,' KM/SEC',
     *  T40,E12.6,' KG')
C
C     FIND DELTA V FROM MARS TO PHOBOS
        R1=RMARS
        R2=RPHOB
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,50) DV,MFUEL
 50     FORMAT ('MARS TO PHOBOS',T20,E12.6,' KM/SEC',
```

```
     * T40,E12.6,' KG')
C
C     FIND DELTA V FROM LMOSS TO MARS
        R1=RLMOSS
        R2=RMARS
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,60) DV,MFUEL
 60     FORMAT ('LMOSS TO MARS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C     FIND DELTA V FROM LUNAR BASE TO LEOSS
        R1=RMOON
        R2=RLEOSS
        MU=MUERTH
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,70) DV,MFUEL
 70     FORMAT ('MOON TO LEOSS',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
C      FIND DELTA V FROM LEOSS TO LUNAR BASE
        R1=RLEOSS
        R2=RMOON
        CALL HOHMAN (R1,R2,MU,DV)
        CALL FUEL (DV,MPAYLD,MFUEL)
        WRITE (6,80) DV,MFUEL
 80     FORMAT ('LEOSS TO MOON',T20,E12.6,' KM/SEC',
     * T40,E12.6,' KG')
C
      STOP
      END
C
      SUBROUTINE HOHMAN (R1,R2,MU,DV)
C
      REAL MU
C
C     PARAMETER DEFINITIONS
C       R1 - RADIUS OF FIRST ORBIT
C       R2 - RADIUS OF SECOND ORBIT
C       MU - GRAVIATIONAL PARAMETER (KM/SEC)
C       DV - DELTA V (KM/SEC)
C       ENERGY - ENERGY REQUIRED FOR TRANSFER ORBIT
C       V1 - VELOCITY NEED AT ORBIT 1 TO GET TO ORBIT 2
C       VC1 - CIRCULAR VELOCITY OF ORBIT 1
C
C     CALCULATIONS
      ENERGY=-MU/(R1+R2)
      V1=SQRT(2*(MU/R1+ENERGY))
      VC1=SQRT(MU/R1)
      DV1=ABS(V1-VC1)
      V2=SQRT(2*(MU/R2+ENERGY))
      VC2=SQRT(MU/R2)
      DV2=ABS(VC2-V2)
      DV=DV1+DV2
      RETURN
      END
C
      SUBROUTINE FUEL (DV,MPAYLD,MFUEL)
C
      REAL MPAYLD,MFUEL,MTOT,ISP
C
```

```
C       INPUT PARAMETERS
        ISP=360
        G=.00980665
C
C       CALCULATIONS
        MTOT=MPAYLD*EXP(DV/(ISP*G))
        MFUEL=MTOT-MPAYLD
C
        RETURN
        END
```

PHOBOS TO LMOSS	.127239E+01 KM/SEC	.867839E+05 KG
PHOBOS TO MARS	.134130E+01 KM/SEC	.924365E+05 KG
MARS TO LMOSS	.801104E-01 KM/SEC	.459021E+04 KG
LMOSS TO PHOBOS	.127239E+01 KM/SEC	.867839E+05 KG
MARS TO PHOBOS	.134130E+01 KM/SEC	.924365E+05 KG
LMOSS TO MARS	.801104E-01 KM/SEC	.459021E+04 KG
MOON TO LEOSS	.389487E+01 KM/SEC	.402783E+06 KG
LEOSS TO MOON	.389487E+01 KM/SEC	.402783E+06 KG

THREE-BODY ANALYSIS USED TO DETERMINE THE ACCELERATIONS ALONG THE X, Y, AND Z - AXES

This program called Axes uses the three-body equations of motion to compute the accelerations along the X, Y, and Z - axes defined in Fig. 3.1. The program initially finds the position vector of the points with respect to Phobos. Then the two position vectors of the center of Phobos and the center of Mars with respect to the point is found. Using these two vectors the acceleration component due to each body is computed (this includes the centripetal acceleration component). All accelerations are then added vectorially. Finally the components of the acceleration toward the center of Phobos and tangential to Phobos are computed.

The input and output units are metric. Kilometers are used instead of meters for all values except the output acceleration values which are in m/sec^2. The output *Positions* are from the point to the center of Phobos. (They are the negative of the position vector of the point with respect to Phobos.) The *Accelerations* are the acceleration vectors with respect to the Phobos coordinate system. The *Total Acceleration* value is the magnitude of the acceleration vector. The *Normal Component* is magnitude of the acceleration toward the center of Phobos. The *Tangential Component* is the acceleration perpendicular to the normal component.

```
      PROGRAM AXES (INPUT,OUTPUT,TAPE 5=INPUT,TAPE 6=OUTPUT)
C
      DIMENSION XP1(82),YP1(82),ZP1(82),XP2(82),YP2(82),ZP2(82),
     *XP3(82),YP3(82),ZP3(82),
     *XM1(82),YM1(82),ZM1(82),XM2(82),YM2(82),ZM2(82),
     *XM3(82),YM3(82),ZM3(82),
     *FXTOT1(82),FYTOT1(82),FZTOT1(82),FXTOT2(82),FYTOT2(82),FZTOT2(82),
     *FXTOT3(82),FYTOT3(82),FZTOT3(82),
     *FTOT1(82),FTOT2(82),FTOT3(82),
     *FCOMP1(82),FCOMP2(82),FCOMP3(82),
     *FTAN1(82),FTAN2(82),FTAN3(82)
C
C     OUTPUT POSITIONS ARE THE NEGATIVE OF THE POSITONS RELATIVE
C     TO PHOBOS AND ARE IN KM
C
C     THE OUTPUT ACCELERATIONS ARE IN M/SEC2
C
      REAL MMASS,MR,MCON,NORMAL
C
C     INPUT VARIABLES
      A=13.5
      B=10.7
      C=9.6
      PHMASS=9.8E15
      MMASS=6.46E23
      G=6.67E-17
      R=9378
C
C     DETERMINE X POINTS
      I=1
      DO 10, N=0,40
C       PLUS X
        X=A+N*0.25
        XP1(I)=X
        YP1(I)=0.0
        ZP1(I)=0.0
C       MINUS X
        XP1(I+41)=-X
        YP1(I+41)=0.0
        ZP1(I+41)=0.0
        I=I+1
 10   CONTINUE
C
C     DETERMINE Y POINTS
      I=1
      DO 20, N=0,40
        Y=B+N*0.25
C       PLUS Y
        XP2(I)=0.0
        YP2(I)=Y
        ZP2(I)=0.0
C       MINUS Y
        XP2(I+41)=0.0
        YP2(I+41)=-Y
        ZP2(I+41)=0.0
        I=I+1
 20   CONTINUE
C
C     DETERMINE Z POINTS
      I=1
      DO 30, N=0,40
```

```
      Z=C+N*0.25
C     PLUS Z
      XP3(I)=0.0
      YP3(I)=0.0
      ZP3(I)=Z
C     MINUS Z
      XP3(I+41)=0.0
      YP3(I+41)=0.0
      ZP3(I+41)=-Z
      I=I+1
 30   CONTINUE
C
C     PHOBOS TO MARS VECTOR
      PHMX=9378
      PHMY=0.0
      PHMZ=0.0
C
C     POINT TO PHOBOS VECTORS
      DO 60, I=1,82
        XP1(I)=-XP1(I)
        YP1(I)=-YP1(I)
        ZP1(I)=-ZP1(I)
C
        XP2(I)=-XP2(I)
        YP2(I)=-YP2(I)
        ZP2(I)=-ZP2(I)
C
        XP3(I)=-XP3(I)
        YP3(I)=-YP3(I)
        ZP3(I)=-ZP3(I)
 60   CONTINUE
C
C     POINT TO MARS VECTORS
      DO 90, I=1,82
        XM1(I)=XP1(I)+PHMX
        YM1(I)=YP1(I)+PHMY
        ZM1(I)=ZP1(I)+PHMZ
C
        XM2(I)=XP2(I)+PHMX
        YM2(I)=YP2(I)+PHMY
        ZM2(I)=ZP2(I)+PHMZ
C
        XM3(I)=XP3(I)+PHMX
        YM3(I)=YP3(I)+PHMY
        ZM3(I)=ZP3(I)+PHMZ
 90   CONTINUE
C
C     COMPUTE CENTRIPETAL ACCELERATION COMPONENT
        OMEGA=(SQRT(G*MMASS/R))/R
        NORMAL=-R*OMEGA**2
C
C     COMPUTE ACCELERATIONS
      DO 120, I=1,82
        PHR=SQRT(XP1(I)**2+YP1(I)**2+ZP1(I)**2)
        MR=SQRT(XM1(I)**2+YM1(I)**2+ZM1(I)**2)
        PHCON=G*PHMASS/PHR**3
        MCON=G*MMASS/MR**3
        FXP=PHCON*XP1(I)
        FYP=PHCON*YP1(I)
        FZP=PHCON*ZP1(I)
        FXM=MCON*XM1(I)
        FYM=MCON*YM1(I)
```

```
      FZM=MCON*ZM1(I)
      FXTOT1(I)=FXP+FXM+NORMAL
      FYTOT1(I)=FYP+FYM
      FZTOT1(I)=FZP+FZM
      FTOT1(I)=SQRT(FXTOT1(I)**2+FYTOT1(I)**2+FZTOT1(I)**2)
      D=XP1(I)*FXTOT1(I)+YP1(I)*FYTOT1(I)+ZP1(I)*FZTOT1(I)
      P=SQRT(XP1(I)**2+YP1(I)**2+ZP1(I)**2)
      FCOMP1(I)=D/P
      FTAN1(I)=SQRT(FTOT1(I)**2-FCOMP1(I)**2)
C
      PHR=SQRT(XP2(I)**2+YP2(I)**2+ZP2(I)**2)
      MR=SQRT(XM2(I)**2+YM2(I)**2+ZM2(I)**2)
      PHCON=G*PHMASS/PHR**3
      MCON=G*MMASS/MR**3
      FXP=PHCON*XP2(I)
      FYP=PHCON*YP2(I)
      FZP=PHCON*ZP2(I)
      FXM=MCON*XM2(I)
      FYM=MCON*YM2(I)
      FZM=MCON*ZM2(I)
      FXTOT2(I)=FXP+FXM+NORMAL
      FYTOT2(I)=FYP+FYM
      FZTOT2(I)=FZP+FZM
      FTOT2(I)=SQRT(FXTOT2(I)**2+FYTOT2(I)**2+FZTOT2(I)**2)
      D=XP2(I)*FXTOT2(I)+YP2(I)*FYTOT2(I)+ZP2(I)*FZTOT2(I)
      P=SQRT(XP2(I)**2+YP2(I)**2+ZP2(I)**2)
      FCOMP2(I)=D/P
      FTAN2(I)=SQRT(FTOT2(I)**2-FCOMP2(I)**2)
C
      PHR=SQRT(XP3(I)**2+YP3(I)**2+ZP3(I)**2)
      MR=SQRT(XM3(I)**2+YM3(I)**2+ZM3(I)**2)
      PHCON=G*PHMASS/PHR**3
      MCON=G*MMASS/MR**3
      FXP=PHCON*XP3(I)
      FYP=PHCON*YP3(I)
      FZP=PHCON*ZP3(I)
      FXM=MCON*XM3(I)
      FYM=MCON*YM3(I)
      FZM=MCON*ZM3(I)
      FXTOT3(I)=FXP+FXM+NORMAL
      FYTOT3(I)=FYP+FYM
      FZTOT3(I)=FZP+FZM
      FTOT3(I)=SQRT(FXTOT3(I)**2+FYTOT3(I)**2+FZTOT3(I)**2)
      D=XP3(I)*FXTOT3(I)+YP3(I)*FYTOT3(I)+ZP3(I)*FZTOT3(I)
      P=SQRT(XP3(I)**2+YP3(I)**2+ZP3(I)**2)
      FCOMP3(I)=D/P
      FTAN3(I)=SQRT(FTOT3(I)**2-FCOMP3(I)**2)
  120 CONTINUE
C
C     PRINT OUT DATA
      DO 140, I=1,82
        IF (I.EQ.1) WRITE (6,200)
  200   FORMAT ('1','PLANE 1- PLUS X')
        IF (I.EQ.42) WRITE (6,205)
  205   FORMAT ('1','PLANE 1 - MINUS X')
        WRITE (6,210) XP1(I),YP1(I),ZP1(I)
  210   FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,220) FXTOT1(I),FYTOT1(I),FZTOT1(I)
  220   FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,230) FTOT1(I)
  230   FORMAT ('TOTAL ACCEL',T15,E12.6)
        WRITE (6,235) FCOMP1(I)
```

```
  235      FORMAT ('NORM COMP',T15,E12.6)
           WRITE (6,237) FTAN1(I)
  237      FORMAT ('TAN COMP',T15,E12.6)
  140   CONTINUE
C
        DO 150, I=1,82
           IF (I.EQ.1) WRITE (6,240)
  240      FORMAT ('1','PLANE 2 - PLUS Y')
           IF (I.EQ.42) WRITE (6,245)
  245      FORMAT ('1','PLANE 2 - MINUS Y')
           WRITE (6,250) XP2(I),YP2(I),ZP2(I)
  250      FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
           WRITE (6,260) FXTOT2(I),FYTOT2(I),FZTOT2(I)
  260      FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
           WRITE (6,270) FTOT2(I)
  270      FORMAT ('TOTAL ACCEL',T15,E12.6)
           WRITE (6,275) FCOMP2(I)
  275      FORMAT ('NORM COMP',T15,E12.6)
           WRITE (6,277) FTAN2(I)
  277      FORMAT ('TAN COMP',T15,E12.6)
  150   CONTINUE
C
        DO 160, I=1,82
           IF (I.EQ.1) WRITE (6,280)
  280      FORMAT ('1','PLANE 1 - PLUS Z')
           IF (I.EQ.42) WRITE (6,285)
  285      FORMAT ('1','PLANE 2 - MINUS Z')
           WRITE (6,290) XP3(I),YP3(I),ZP3(I)
  290      FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
           WRITE (6,300) FXTOT3(I),FYTOT3(I),FZTOT3(I)
  300      FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
           WRITE (6,310) FTOT3(I)
  310      FORMAT ('TOTAL ACCEL',T15,E12.6)
           WRITE (6,315) FCOMP3(I)
  315      FORMAT ('NORM COMP',T15,E12.6)
           WRITE (6,317) FTAN3(I)
  317      FORMAT ('TAN COMP',T15,E12.6)
  160   CONTINUE
C
        STOP
        END
```

TWO-BODY ANALYSIS USED TO DETERMINE THE ACCELERATIONS ALONG THE X, Y, AND Z - AXES

This program called Axes uses the two-body equations of motion to compute the accelerations due to Phobos only. The points for which the accelerations are computed are along the X, Y, and Z - axes and are defined in Fig. 3.1. The program initially finds the position vector of the points with respect to Phobos. Then the position vector of the center of Phobos with respect to the point is found. Using this vector the acceleration component due to Phobos only is computed (this does not include the centripetal acceleration component due to the orbit about Mars).

The input and output units are in metric units. Kilometers are used instead of meters for all values except the output acceleration values which are in m/sec^2. The output *Positions* are from the point to the center of Phobos. (They are the negative of the position vector with respect to Phobos.) The *Total Acceleration* value is the magnitude of the acceleration vector.

```
      PROGRAM AXES2 (INPUT,OUTPUT,TAPE 5=INPUT,TAPE 6=OUTPUT)
C
      DIMENSION XP1(82),YP1(82),ZP1(82),XP2(82),YP2(82),ZP2(82),
     *XP3(82),YP3(82),ZP3(82),
     *FTOT1(82),FTOT2(82),FTOT3(82)
C
C     OUTPUT POSITIONS ARE THE NEGATIVE OF THE POSITONS RELATIVE
C     TO PHOBOS AND ARE IN KM
C
C     THE OUTPUT ACCELERATIONS ARE IN M/SEC2
C
C     INPUT VARIABLES
      A=13.5
      B=10.7
      C=9.6
      PHMASS=9.8E15
      G=6.67E-17
C
C     DETERMINE X POINTS
      I=1
      DO 10, N=0,40
C       PLUS X
        X=A+N*0.25
        XP1(I)=X
        YP1(I)=0.0
        ZP1(I)=0.0
C       MINUS X
        XP1(I+41)=-X
        YP1(I+41)=0.0
        ZP1(I+41)=0.0
        I=I+1
 10   CONTINUE
C
C     DETERMINE Y POINTS
      I=1
      DO 20, N=0,40
        Y=B+N*0.25
C       PLUS Y
        XP2(I)=0.0
        YP2(I)=Y
        ZP2(I)=0.0
C       MINUS Y
        XP2(I+41)=0.0
        YP2(I+41)=-Y
        ZP2(I+41)=0.0
        I=I+1
 20   CONTINUE
C
C     DETERMINE Z POINTS
      I=1
      DO 30, N=0,40
        Z=C+N*0.25
C       PLUS Z
        XP3(I)=0.0
        YP3(I)=0.0
        ZP3(I)=Z
C       MINUS Z
        XP3(I+41)=0.0
        YP3(I+41)=0.0
        ZP3(I+41)=-Z
        I=I+1
```

```
 30   CONTINUE
C
C     POINT TO PHOBOS VECTORS
      DO 60, I=1,82
        XP1(I)=-XP1(I)
        YP1(I)=-YP1(I)
        ZP1(I)=-ZP1(I)
C
        XP2(I)=-XP2(I)
        YP2(I)=-YP2(I)
        ZP2(I)=-ZP2(I)
C
        XP3(I)=-XP3(I)
        YP3(I)=-YP3(I)
        ZP3(I)=-ZP3(I)
 60   CONTINUE
C
C     COMPUTE ACCELERATIONS
      DO 120, I=1,82
        PHR=SQRT(XP1(I)**2+YP1(I)**2+ZP1(I)**2)
        PHCON=G*PHMASS/PHR**3
        FXP=PHCON*XP1(I)
        FYP=PHCON*YP1(I)
        FZP=PHCON*ZP1(I)
        FTOT1(I)=SQRT(FXP**2+FYP**2+FZP**2)
C
        PHR=SQRT(XP2(I)**2+YP2(I)**2+ZP2(I)**2)
        PHCON=G*PHMASS/PHR**3
        FXP=PHCON*XP2(I)
        FYP=PHCON*YP2(I)
        FZP=PHCON*ZP2(I)
        FTOT2(I)=SQRT(FXP**2+FYP**2+FZP**2)
C
        PHR=SQRT(XP3(I)**2+YP3(I)**2+ZP3(I)**2)
        PHCON=G*PHMASS/PHR**3
        FXP=PHCON*XP3(I)
        FYP=PHCON*YP3(I)
        FZP=PHCON*ZP3(I)
        FTOT3(I)=SQRT(FXP**2+FYP**2+FZP**2)
 120  CONTINUE
C
C     PRINT OUT DATA
      DO 140, I=1,82
        IF (I.EQ.1) WRITE (6,200)
 200    FORMAT ('1','PLANE 1- PLUS X')
        IF (I.EQ.42) WRITE (6,205)
 205    FORMAT ('1','PLANE 1 - MINUS X')
        WRITE (6,210) XP1(I),YP1(I),ZP1(I)
 210    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,230) FTOT1(I)
 230    FORMAT ('TOTAL ACCEL',T15,E12.6)
 140  CONTINUE
C
      DO 150, I=1,82
        IF (I.EQ.1) WRITE (6,240)
 240    FORMAT ('1','PLANE 2 - PLUS Y')
        IF (I.EQ.42) WRITE (6,245)
 245    FORMAT ('1','PLANE 2 - MINUS Y')
        WRITE (6,250) XP2(I),YP2(I),ZP2(I)
 250    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,270) FTOT2(I)
 270    FORMAT ('TOTAL ACCEL',T15,E12.6)
```

```
  150   CONTINUE
C
        DO 160, I=1,82
          IF (I.EQ.1) WRITE (6,280)
  280     FORMAT ('1','PLANE 1 - PLUS Z')
          IF (I.EQ.42) WRITE (6,285)
  285     FORMAT ('1','PLANE 2 - MINUS Z')
          WRITE (6,290) XP3(I),YP3(I),ZP3(I)
  290     FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
          WRITE (6,310) FTOT3(I)
  310     FORMAT ('TOTAL ACCEL',T15,E12.6)
  160   CONTINUE
C
        STOP
        END
```

THREE-BODY ANALYSIS USED TO DETERMINE THE ACCELERATIONS IN FOUR PLANES

This program called Axes uses the three-body equations of motion to compute the accelerations in the planes defined in Fig. 3.2. The program initially finds the position vector of the points with respect to Phobos. Then the two position vectors of the center of Phobos and the center of Mars with respect to the point is found. Using these two vectors the acceleration component due to each body is computed (this includes the centripetal acceleration component). All accelerations are then added vectorially.

The input and output units are metric. Kilometers are used instead of meters for all values except the output acceleration values which are in m/sec^2. The plane numbers are defined the same way as in Fig. 3.2. The output *Positions* are from the point to the center of Phobos. (They are the negative of the position vector with respect to Phobos.) The *Accelerations* are the acceleration vectors with respect to the Phobos coordinate system. The *Total Acceleration* values is the magnitude of the acceleration vector.

```
      PROGRAM PLANES (INPUT,OUTPUT,TAPE 5=INPUT,TAPE 6=OUTPUT)
C
      DIMENSION XP1(56),YP1(56),ZP1(56),XP2(42),YP2(42),ZP2(42),
     *XP3(34),YP3(34),ZP3(34),XP4(34),YP4(34),ZP4(34),
     *XM1(56),YM1(56),ZM1(56),XM2(42),YM2(42),ZM2(42),
     *XM3(34),YM3(34),ZM3(34),XM4(34),YM4(34),ZM4(34),
     *FXTOT1(56),FYTOT1(56),FZTOT1(56),FXTOT2(42),FYTOT2(42),FZTOT2(42),
     *FXTOT3(34),FYTOT3(34),FZTOT3(34),FXTOT4(34),FYTOT4(34),FZTOT4(34),
     *FTOT1(56),FTOT2(42),FTOT3(34),FTOT4(34)
C
C     OUTPUT POSITIONS ARE THE NEGATIVE OF THE POSITONS RELATIVE
C     TO PHOBOS AND ARE IN KM
C
C     THE OUTPUT ACCELERATIONS ARE IN M/SEC2
C
      REAL MMASS,MR,MCON,NORMAL
C
C     INPUT VARIABLES
      A=13.5
      B=10.7
      C=9.6
      PHMASS=9.8E15
      MMASS=6.46E23
      G=6.67E-17
      R=9378
C
C     DETERMINE POINTS IN PLANE 1
      I=1
      DO 10, N=1,28
        X=N-14.5
        XP1(I)=X
        YP1(I)=0.0
        ZP1(I)=SQRT(C**2*(1-X**2/A**2))
        I=I+1
        XP1(I)=X
        YP1(I)=0.0
        ZP1(I)=-SQRT(C**2*(1-X**2/A**2))
        I=I+1
 10   CONTINUE
C
C     DETERMINE POINTS IN PLANE 2
      I=1
      DO 20, N=1,21
        Y=N-11.7
        XP2(I)=0.0
        YP2(I)=Y
        ZP2(I)=SQRT(C**2*(1-Y**2/B**2))
        I=I+1
        XP2(I)=0.0
        YP2(I)=Y
        ZP2(I)=-SQRT(C**2*(1-Y**2/B**2))
        I=I+1
 20   CONTINUE
C
C     DETERMINE POINTS IN PLANES 3 AND 4
      I=1
      XLIMIT=SQRT(A**2*B**2/(A**2+B**2))
      DO 30, N=1,17
        X=N-(1+XLIMIT)
        XP3(I)=X
        YP3(I)=X
```

```
          XP4(I)=X
          YP4(I)=-X
          ZP3(I)=SQRT(C**2*(1-X**2/A**2-X**2/B**2))
          ZP4(I)=ZP3(I)
          I=I+1
          XP3(I)=X
          YP3(I)=X
          XP4(I)=X
          YP4(I)=-X
          ZP3(I)=-SQRT(C**2*(1-X**2/A**2-X**2/B**2))
          ZP4(I)=ZP3(I)
          I=I+1
 30     CONTINUE
C
C       PHOBOS TO MARS VECTOR
        PHMX=9378
        PHMY=0.0
        PHMZ=0.0
C
C       POINT TO PHOBOS VECTORS
        DO 40, I=1,56
          XP1(I)=-XP1(I)
          YP1(I)=-YP1(I)
          ZP1(I)=-ZP1(I)
 40     CONTINUE
C
        DO 50, I=1,42
          XP2(I)=-XP2(I)
          YP2(I)=-YP2(I)
          ZP2(I)=-ZP2(I)
 50     CONTINUE
C
        DO 60, I=1,34
          XP3(I)=-XP3(I)
          YP3(I)=-YP3(I)
          ZP3(I)=-ZP3(I)
          XP4(I)=-XP4(I)
          YP4(I)=-YP4(I)
          ZP4(I)=-ZP4(I)
 60     CONTINUE
C
C       POINT TO MARS VECTORS
        DO 70, I=1,56
          XM1(I)=XP1(I)+PHMX
          YM1(I)=YP1(I)+PHMY
          ZM1(I)=ZP1(I)+PHMZ
 70     CONTINUE
C
        DO 80, I=1,42
          XM2(I)=XP2(I)+PHMX
          YM2(I)=YP2(I)+PHMY
          ZM2(I)=ZP2(I)+PHMZ
 80     CONTINUE
C
        DO 90, I=1,34
          XM3(I)=XP3(I)+PHMX
          YM3(I)=YP3(I)+PHMY
          ZM3(I)=ZP3(I)+PHMZ
          XM4(I)=XP4(I)+PHMX
          YM4(I)=YP4(I)+PHMY
          ZM4(I)=ZP4(I)+PHMZ
 90     CONTINUE
```

```
C
C      CENTRIPETAL ACCELERATION COMPONENT
         OMEGA=(SQRT(G*MMASS/R))/R
         NORMAL=-R*OMEGA**2
C
C      COMPUTE ACCELERATIONS
       DO 100, I=1,56
         PHR=SQRT(XP1(I)**2+YP1(I)**2+ZP1(I)**2)
         MR=SQRT(XM1(I)**2+YM1(I)**2+ZM1(I)**2)
         PHCON=G*PHMASS/PHR**3
         MCON=G*MMASS/MR**3
         FXP=PHCON*XP1(I)
         FYP=PHCON*YP1(I)
         FZP=PHCON*ZP1(I)
         FXM=MCON*XM1(I)
         FYM=MCON*YM1(I)
         FZM=MCON*ZM1(I)
         FXTOT1(I)=FXP+FXM+NORMAL
         FYTOT1(I)=FYP+FYM
         FZTOT1(I)=FZP+FZM
         FTOT1(I)=SQRT(FXTOT1(I)**2+FYTOT1(I)**2+FZTOT1(I)**2)
 100   CONTINUE
C
       DO 110, I=1,42
         PHR=SQRT(XP2(I)**2+YP2(I)**2+ZP2(I)**2)
         MR=SQRT(XM2(I)**2+YM2(I)**2+ZM2(I)**2)
         PHCON=G*PHMASS/PHR**3
         MCON=G*MMASS/MR**3
         FXP=PHCON*XP2(I)
         FYP=PHCON*YP2(I)
         FZP=PHCON*ZP2(I)
         FXM=MCON*XM2(I)
         FYM=MCON*YM2(I)
         FZM=MCON*ZM2(I)
         FXTOT2(I)=FXP+FXM+NORMAL
         FYTOT2(I)=FYP+FYM
         FZTOT2(I)=FZP+FZM
         FTOT2(I)=SQRT(FXTOT2(I)**2+FYTOT2(I)**2+FZTOT2(I)**2)
 110   CONTINUE
C
       DO 120, I=1,34
         PHR=SQRT(XP3(I)**2+YP3(I)**2+ZP3(I)**2)
         MR=SQRT(XM3(I)**2+YM3(I)**2+ZM3(I)**2)
         PHCON=G*PHMASS/PHR**3
         MCON=G*MMASS/MR**3
         FXP=PHCON*XP3(I)
         FYP=PHCON*YP3(I)
         FZP=PHCON*ZP3(I)
         FXM=MCON*XM3(I)
         FYM=MCON*YM3(I)
         FZM=MCON*ZM3(I)
         FXTOT3(I)=FXP+FXM+NORMAL
         FYTOT3(I)=FYP+FYM
         FZTOT3(I)=FZP+FZM
         FTOT3(I)=SQRT(FXTOT3(I)**2+FYTOT3(I)**2+FZTOT3(I)**2)
 120   CONTINUE
C
       DO 130, I=1,34
         PHR=SQRT(XP4(I)**2+YP4(I)**2+ZP4(I)**2)
         MR=SQRT(XM4(I)**2+YM4(I)**2+ZM4(I)**2)
         PHCON=G*PHMASS/PHR**3
         MCON=G*MMASS/MR**3
```

```
      FXP=PHCON*XP4(I)
      FYP=PHCON*YP4(I)
      FZP=PHCON*ZP4(I)
      FXM=MCON*XM4(I)
      FYM=MCON*YM4(I)
      FZM=MCON*ZM4(I)
      FXTOT4(I)=FXP+FXM+NORMAL
      FYTOT4(I)=FYP+FYM
      FZTOT4(I)=FZP+FZM
      FTOT4(I)=SQRT(FXTOT4(I)**2+FYTOT4(I)**2+FZTOT4(I)**2)
 130  CONTINUE
C
C     PRINT OUT DATA
      WRITE (6,200)
 200  FORMAT ('1','PLANE 1')
      DO 140, I=1,56
        WRITE (6,210) XP1(I),YP1(I),ZP1(I)
 210    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,220) FXTOT1(I),FYTOT1(I),FZTOT1(I)
 220    FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,230) FTOT1(I)
 230    FORMAT ('TOTAL ACCEL',T15,E12.6)
 140  CONTINUE
C
      WRITE (6,240)
 240  FORMAT ('1','PLANE 2')
      DO 150, I=1,42
        WRITE (6,250) XP2(I),YP2(I),ZP2(I)
 250    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,260) FXTOT2(I),FYTOT2(I),FZTOT2(I)
 260    FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,270) FTOT2(I)
 270    FORMAT ('TOTAL ACCEL',T15,E12.6)
 150  CONTINUE
C
      WRITE (6,280)
 280  FORMAT ('1','PLANE 3')
      DO 160, I=1,34
        WRITE (6,290) XP3(I),YP3(I),ZP3(I)
 290    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,300) FXTOT3(I),FYTOT3(I),FZTOT3(I)
 300    FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,310) FTOT3(I)
 310    FORMAT ('TOTAL ACCEL',T15,E12.6)
 160  CONTINUE
C
      WRITE (6,320)
 320  FORMAT ('1','PLANE 4')
      DO 170, I=1,34
        WRITE (6,330) XP4(I),YP4(I),ZP4(I)
 330    FORMAT ('0','POSITION',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,340) FXTOT4(I),FYTOT4(I),FZTOT4(I)
 340    FORMAT ('ACCEL',T10,E12.6,T25,E12.6,T40,E12.6)
        WRITE (6,350) FTOT4(I)
 350    FORMAT ('TOTAL ACCEL',T15,E12.6)
 170  CONTINUE
C
      STOP
      END
```

APPENDIX B - ACRONYMS

ACRONYMS

AI - Artificial Intelligence

AM - Application Module

EVA - Extra Vehicular Activity

FV - Flying Vehicle

JSC - Johnson Space Center in Houston

LEO - Low Earth Orbit

LEOSS - Low Earth Orbit Space Station

LIL-TLEV - Lunar International Laboratory-Translunar Exploration Vehicle

LMO - Low Mars Orbit

LMOSS - Low Mars Orbit Space Station

LSM - Linear Synchronous Motors

MLV - Magnetic Levitation Vehicle

MMU - Manned Maneuvering Unit

MRMS - Mobile Remote Manipulating System

NASA - National Aeronautics and Space Administration

PC - Personal Computer

PDR - Preliminary Design Review

PPPM - Primary Power Plant Module

RPV - Remote Placement Vehicle

REM - Roentgen-Equivalent-Man

RFP - Request For Proposal

RMPM - Raw Material Processing Module

RMS - Remote Manipulating System

SBVM - Storage/Base Vehicle Module

SHHM - Safe Haven/Habitation Module

SM - System Module

SSAS - Small Scale Anchor System

SSU - Space Scooter Unit

TSS - Texas Space Systems

UT - University of Texas at Austin